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VOLUME XLIX NUMBER 3

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Solar Observatory of the Carnegie Institution of Washington

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Yerkes Observatory of the University of Chicago

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Ryerson Physical Laboratory of the University of Chicago

APRIL 1919

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VOLUME XLIX APRIL 1919 NUMBER 3

A PHOTO-ELECTRIC DETERMINATION OF THE BRIGHTNESS OF THE CORONA AT THE ECLIPSE OF JUNE 8, 1918

By JACOB KUNZ and JOEL STEBBINS

A general account of the eclipse expedition to Rock Springs from the University of Illinois has been given in *Popular Astronomy*, **26,** 665, 1918. It was our purpose to secure accurate measures of the light of the corona as it affects a photo-electric cell, which if successful would form the basis of further studies of the corona at subsequent eclipses, an excellent opportunity for which is probably coming in 1923. A glance at the results of photometric work at past eclipses shows a curious discrepancy between the work of different investigators, and the reported values of the coronal light indicated either a great change between one eclipse and the next, or that the methods and instruments used were so different that it is doubtful whether the observers were all measuring the same thing. It was also true that in most cases the photometry of the eclipse was only an incidental feature of the program, and no great effort was made to get the best possible results. For these reasons it seemed to us that it would be worth while to devote our entire energies to measuring the total light of the corona, and the use of the photo-electric cell promised distinct advantages over visual or photographic methods.

Tests made some months in advance indicated that several photo-electric cells which we had on hand would give satisfactory measures of lights as faint as the crescent moon, an illumination at the cell equal to only a few hundredths of a candle-meter. These measures were possible with a d'Arsonval galvanometer of no great sensitivity, and it seemed probable that the corona would be bright enough to be measured with such equipment as we could set up at a temporary station, far from the conveniences of a laboratory.

Our procedure was to expose a photo-electric cell directly to the corona at the time of totality, and compare the galvanometer-deflection then obtained with the deflection caused by standard lights at known distances before and after the eclipse. As the cell was constant in its action and would give the same current for the same light for several days in succession, there was no need for manipulating the lamps during the precious seconds of totality. It was also proposed to compare the corona with the moon, which would serve as a permanent standard of light, and also with a definite area of the sky both during the eclipse and in full sunshine. This last comparison would give some estimate of the possibility of using the photo-electric cell in attempts to detect the corona without an eclipse.

Each of the photo-electric cells which we ordinarily employ has a glass bulb of about 25 mm diameter, and as the sensitive surface covers nearly a hemisphere we may take a circular area of 25 mm diameter as the portion sensitive to light. The two cells actually used, however, had a diameter of 40 mm and were mounted in exactly the same way in two similar tubes, which made a double-barreled arrangement. Each cell was placed in a box with a 25-mm circular opening, which was central at the end of a tube 100 mm in diameter and about 122 cm long. At the upper end of this tube there was a diaphragm 89 mm in aperture, which was at an effective distance of 127 cm from the sensitive cell. From these dimensions it follows that any point on the cell was illuminated by a circle of sky with radius = arc tan $\frac{4{\cdot}45}{127} = 2°0$. It also may be derived that the clear field of the apparatus was 3° in diameter,

which was enough to include all of the corona and to allow for the diurnal motion during the minute and a half of totality. It was therefore unnecessary to provide any driving arrangement, and the tubes were simply pointed at the sun's position at the middle of the eclipse. A series of diaphragms were inserted at intervals of 15 cm in each tube, carefully arranged, so that no part of the cell would receive light from the side of the tube.

The twin tubes were fastened to an equatorial mounting, two stops provided in declination, which allowed just 8° motion. During totality the tubes were turned back and forth from the sun to the sky 8° north, which was ample to take the corona safely out of the field.

Each cell-box was readily detached from its tube and could be placed on a photometer bench for measures of the standard lamps. No lenses or windows of any kind were interposed between the cell and the light-source to be measured, though of course there was the glass wall of the cell, which cannot be eliminated.

The photometer bench at the station was a rack fastened to the side of the building, and the distance from light to cell could be varied from 1 to 3 meters. Between the light and the cell was a set of telescoping tubes with proper diaphragms, which kept out all stray light.

For source of potential for the photo-electric cells we used some seventy-five small flash-light batteries of three cells each, giving a total of about 300 volts. These commercial batteries are quite good enough for many testing purposes, and we prefer them to storage cells, which require constant attention. For the needs at the temporary station they served the purpose admirably.

Altogether we had four galvanometers available, three of Leeds & Northrup and one by Weston. The two definitely used were a Leeds & Northrup Type R instrument with a constant of 6×10^{-10} amperes for 1 mm deflection at 1-meter scale-distance, and the other with a similar constant of 2×10^{-10} amperes. As used with damping shunts, the times to secure full deflection were 6 and 10 seconds respectively. Each galvanometer has a plane mirror and was used with a view telescope and scale at 2 meters. The circuit for each cell consisted simply of the battery, photo-electric cell,

galvanometer, and a guard resistance of 100,000 ohms, all connected in series. Exposure of the cell to light gives the current to be measured, and the high resistance in circuit obviates the danger of spoiling a cell by too high a potential. The critical or glowing voltage of a cell is some ten volts higher in the dark than in a strong light.

Various investigators have had difficulty with a non-linear relation between light and current for the photo-electric cell. One of us has already shown[1] that for our cells the current is very nearly

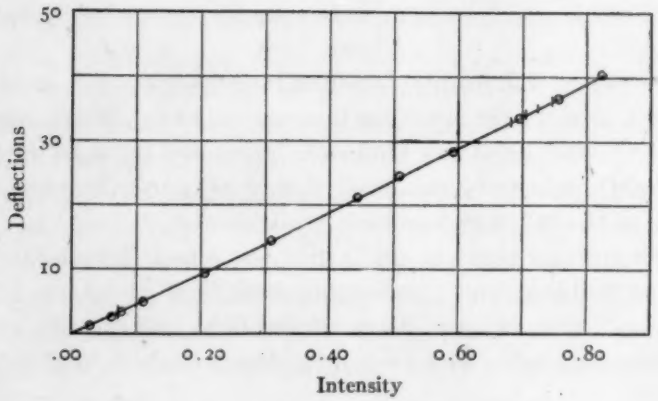


FIG. 1.—Calibration of photo-electric cell

proportional to the light, and for faint sources like the stars this is especially the case. We give herewith the calibration of the cell, which was made on June 8 shortly after the eclipse, and which was actually used for determining the light of the corona. In Fig. 1 the intensities are on the basis of the inverse square of the distance from lamp to cell.

The color-sensibilities of photo-electric cells have not been thoroughly studied in general, but we have definite results for the potassium cell which was used at the eclipse. Fig. 2 shows the curve as determined by Mr. T. Shinomiya in our physics laboratory. The energy of the beam of light which affected the cell was measured with a thermo-couple, and the results are all reduced to equal

[1] *Astrophysical Journal*, **45**, 69, 1917.

energies. The curve is not yet complete in the ultra-violet, as the energy becomes so small as to require a more sensitive arrangement for its measurement. From rough measures and various considerations we know that this cell is very insensitive to radiation of wave-length shorter than 4000 A, and the effective maximum

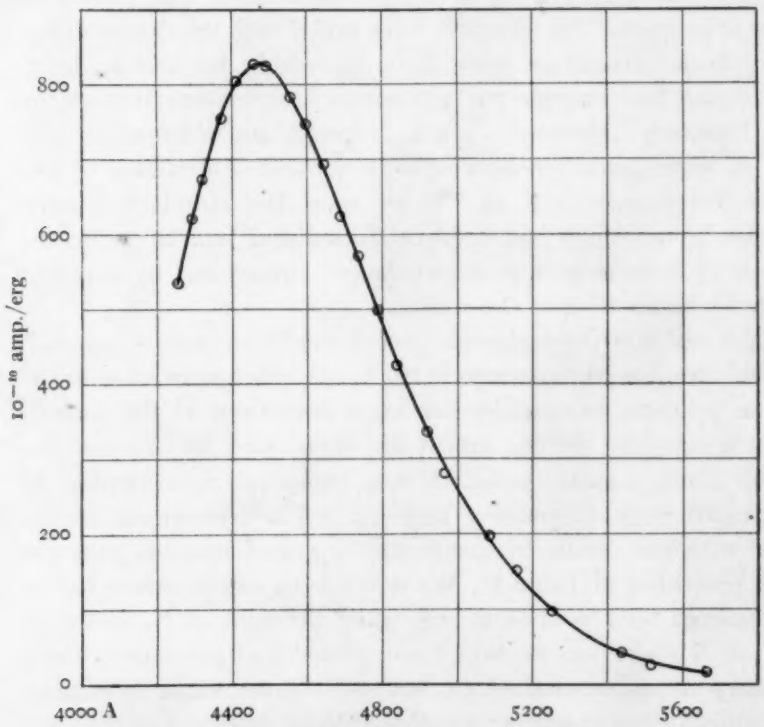


FIG. 2.—Color-sensibility curve of a potassium photo-electric cell

sensibility of the cell is therefore toward the red from the maximum of the ordinary unstained photographic plate. The "color-equation" of the potassium cell used in our stellar photometry is 0.86 magnitude.

Our main reliance for a standard of light was an amyl-acetate candle, or Hefner lamp, the same as used by Stebbins and Brown in measures of the light of the moon by means of a selenium cell.[1]

[1] *Astrophysical Journal*, **26**, 326, 1907.

The wick is of 8 mm diameter, and the height of the flame is regulated to 40 mm. The amyl acetate was purified by distillation between 137° and 143° C. Although this candle is much more troublesome to use than a low-voltage electric lamp, nevertheless it is easy to reproduce after a long period of time, and seems to be the best source to rely upon for comparisons of the corona at different eclipses. No measures were taken with the candle unless it had been burning for some time, preferably for half an hour.

We also had two electric pyrometer lamps, secured from the Nela Research Laboratory, which, although not designed for this kind of work, served very well for tests and calibrations of the photo-electric cells and as checks upon the standard candle. Another lamp, which had been calibrated and sent to us by the Bureau of Standards, was unfortunately burned out by accident before we had used it at the station.

Since much of the preliminary work was experimental, we shall give only the intercomparisons of the lamps which were made at the station, as these were under the exact conditions at the time of the eclipse. The electric lamps are designated by N_1 and N_2, require about 4 volts, and each was burned at 0.60 ampere, as determined with a precision ammeter. The comparison of the lamps with the candle by means of the potassium cells gave the ratios presented in Table I. We adopt 0.93 candle-power for N_1 as measured by a potassium cell, while the light of N_2 was 0.79 that of N_1. As far as accidental errors are concerned, these measures are quite satisfactory, but we have not made an exhaustive study of the candle at widely different dates. For the electric lamps, N_1 and N_2, the measures were really only a check upon the readings of the ammeter, as a small change in the current was as readily determined by the light-effect shown by the galvanometer as by the motion of the ammeter needle. We expect to keep all of these standards of light for the next eclipse.

We were able to compare our candle with an electric lamp which Mr. Parkhurst brought over from Green River to our station on June 5. Measured with cell K113 his lamp at 5.4 volts gave 10.4 candles, as compared with the Bureau of Standards visual tests, which gave 4.65 candles at the same voltage. The differ-

ence is due to the filament of this electric lamp being much whiter than the amyl-acetate flame, and the blue-sensitive photo-electric cell naturally gives a higher value than the eye does when a white light is expressed in terms of a yellow one.

TABLE I

COMPARISON OF LAMPS, CELL K113

Date	N_1/Candle	Residual	Date	N_2/N_1	Residual
June 4.....	0.92	−0.01	June 6.....	0.78	−0.01
June 6.....	.93	.00	June 8.....	.79	.00
	.92	− .01		.79	.00
	.93	.00		.78	− .01
June 8.....	.93	.00		.78	− .01
	.92	− .01		.78	− .01
	.94	+ .01	June 9.....	.80	+ .01
	.96	+ .03		.79	.00
June 9.....	.93	.00		.79	.00
	.92	− .01		.80	+ .01
Mean...	0.93	±0.008	Mean...	0.79	±0.006

COMPARISON OF LAMPS, CELL K59

	N_1/Candle	N_2/N_1
June 9.....	0.94	0.80
	0.92	.80
	.....	.80
	.....	.80
Mean.....	0.93	0.80

The program during totality provided for a first exposure to the corona and sky background, then to the sky 8° north of the sun, back to the corona, and so on, with one stop to check the zero of the galvanometer. As full galvanometer deflection was secured in ten seconds or less, it was convenient to take readings every ten seconds, and the photometer tubes were moved at each count of ten and then left undisturbed. The metronome used for timing was regulated to beat 100 times in the 95 seconds of totality, and we thus got in ten counts of ten each, the half-second lost in each ten being unnoticed. The start at second contact was probably quite accurate, as the sun reappeared within one second of the hundredth count.

The exposures to the sky 8° north of the sun required that there should be no clouds in that direction, and we were very fortunate in that the clear space just before totality came from the northwest, and during the critical time the sky was perfect for our purpose. It would have been impossible to change at the last minute and turn the instrument in any direction but north. As very little of the sky illumination during a total eclipse comes from the corona, it is safe to consider the sky background close to the sun to be the same as at some distance away.

The two cells which were to be used were the potassium cell, K113, in a circuit of moderate sensitiveness, and a rubidium cell which had a voltage applied almost up to the glowing-point, so as to get the maximum effect. A false start just before second contact flashed the rubidium cell, and it could not be brought back into adjustment in the short time, so that this half of the program was lost. The safe side of the combination worked perfectly, however, and Mr. Kunz found that the readings were made with perfect ease. Our advance estimate was that the initial deflection from the corona plus sky background would be 5 scale-divisions with the potassium cell and 12 with the rubidium. We were prepared to observe deflections say ten times smaller and up to fifty times larger than the estimate, and we felt safe that the readings would not go off the scale. The actual result was a deflection of 33 divisions with the potassium cell, or nearly seven times the amount estimated.

Table II gives the readings and results during the eclipse. In the first column are the times of reading, counting 100 to the duration of totality. The second column is self-explanatory. The readings in the third column are just as they were put down at the time, the observer noting afterward that where no tenths were recorded the whole division was exact within one- or two-tenths. These readings show a gradual shift of the zero from 90.0 to 89.5 during the course of the measures, and this has been allowed for in the deflections in the next column. This would have been called a large shift of the zero under the preliminary conditions, but altogether it was fortunate that nothing worse came up during totality. The fifth, sixth, and seventh columns were derived from the calibra-

tion shown in Fig. 1, where the four deflections from the corona and sky, also the sky alone, are marked on the curve. Considering the first deflection of 33.0 divisions, it is found that this corresponded to an illumination of 0.682, the unit being the light from N_1 at 1 meter. Subtracting the sky effect of 0.072 in the same unit, we have the corona equal to 0.610 of N_1 at a meter. Multiplying this by 0.93 and rounding off one place we get 0.57 candle-meters for the corona.

TABLE II

OBSERVATIONS DURING TOTALITY

TIME	EXPOSURE TO	GALVANOMETER READING	DEFLECTION	UNIT = N_1 AT 1 METER			CORONA IN CANDLE-METERS
				Corona + Sky	Sky	Corona Alone	
		div.	div.				
0...	Dark	90	0.0	.....	.....	.....	.....
10...	Corona+Sky	123	33.0	0.682	0.072	0.610	0.57
20...	Sky	93	3.1	.....	.....	.....	.....
30...	Corona+Sky	125	35.1	0.723	0.072	0.651	0.61
40...	Sky	93	3.1	.....	.....	.....	.....
50...	Corona+Sky	124	34.2	0.705	0.072	0.633	0.59
60...	Dark	89.8	0.0	.....	.....	.....	.....
70...	Sky	92.8	3.1	.....	.....	.....	.....
80...	Corona+Sky	126	36.3	0.746	0.077	0.669	0.62
90...	Sky	93.2	3.6	.....	.....	.....	.....
100...	Dark	89.5	0.0	.....	.....	.....	.....
Mean	.....	.....	.....	.....	.....	.....	0.60

The differences between the four values in the last column are considered to be real, but we are unable to say with certainty whether or not the variation is due to the motion of the moon over the inner corona and chromosphere. From the report of our assistants, who were in the open, there was absolutely no haze near the sun during totality, so we think it improbable that the differences are due to variable transparency of the atmosphere. As photometric measures go, however, the measures agree well enough, with a range of less than 10 per cent. If it had been possible to carry out our complete program we should have had eight readings on the corona instead of four, and these slight variations would have been checked; but for the mean value in candle-meters the four readings are quite sufficient.

We may now consider additional comparison measures which were made at the station before and after the eclipse. It was intended to take a long series of readings on the brightness of the sky as the eclipse came on, but the presence of clouds prevented this. We did obtain, however, a few exposures to the clear sky shortly after first contact. With an aperture of 4.57 mm at the upper end of the photometer tube, the potassium cell was exposed at G.M.T. 10^h16^m to the sky 8° north of the sun. The mean of several deflections was 47.2 divisions, as compared with 31.5 divisions, the average deflection from the corona. For this purpose we may assume a linear relation between light and current. It is convenient to reduce the sky measure to that of a circle of $\frac{1}{2}°$ diameter, and a factor 0.93 is introduced because about 7 per cent of the sun's disk was covered by the moon at the time of measurement. We have then

$$\frac{\text{Corona}}{\text{Sky circle } \frac{1}{2}° \text{ diameter}} = 0.93 \, \frac{31.5}{47.2} \left(\frac{0.457}{127 \tan \frac{1}{2}°} \right)^2 = 0.105,$$

or the corona gave one-tenth the light of an area of daylight sky of the apparent size of the sun and 8° distant. This refers to the Wyoming sky, which was clear and blue at the time, and the altitude of the station was about 6500 ft. above sea-level.

From the readings in Table II the 4° circle of sky gave a deflection of 3.1 divisions, or one-tenth the effect of the corona. Reducing to a circle of $\frac{1}{2}°$ diameter, this makes the corona 640 times as bright as that area of the sky during totality. It follows, therefore, that the sky intensity was reduced $\frac{640}{0.105} = 6100$-fold by the moon's shadow. As the decrease from sun to full moon is something like one hundred times greater than this, and the corona is fainter than the moon, it follows that less than 1 per cent of the sky illumination during totality came from the corona.

It was planned to get measures of the full moon before leaving Urbana for the West, but bad weather prevailed. We did succeed in getting test measures at Rock Springs on the waning moon on two mornings just before dawn. However, we were especially fortunate in having two clear nights on our return to Urbana two

weeks after the eclipse, and the moon was measured on June 23 just before it entered the penumbra of the earth's shadow. This was as nearly an uneclipsed full moon as can ever be observed.

Table III gives the measures of the moon and the results. The fourth column contains the observed values of the moon's light, the fifth the reduction to mean distance of moon and sun, and the sixth the correction for atmospheric absorption. The numbers in the seventh column are derived from the fourth column by applying the logarithmic corrections in the fifth and sixth. In the eighth column the phase is counted each way from the point opposite the sun, positive after full moon. At the foot of the table are given the measure on the corona and the comparison with the full moon.

TABLE III

OBSERVATIONS OF THE MOON

Date	G.M.T.	Zenith Distance	Moon's Light in Candle-Meters	Log. Reduction to Mean Distance	Log. Correction to No Atmosphere	Corrected Moon's Light in Candle-Meters	Mean in Candle-Meters	Phase	Absorption Factor
1918 June 3	22h 30m	69°.5	0.017	9.967	0.635	0.068	.....	.....	....
	22 35	68.6	.020	9.967	0.608	.075	.....	.....	....
	22 39.5	67.7	.018	9.967	0.582	.064	.....	.....	....
	22 46	66.6	.017	9.967	0.550	.056	0.066	+120°	2.5
June 4	22 18	78.2	.005	9.968	0.747	.026	.....	.....	....
	22 28	76.3	.005	9.968	0.662	.021	.....	.....	....
	22 59	70.7	.011	9.968	0.484	0.031	0.026	+134	1.8
June 22	18 07	66.6	.58	0.015	0.444	1.67	.....	.....	....
	18 52	70.2	.51	0.015	0.524	1.77	.....	.....	....
	19 14	72.1	.45	0.015	0.578	1.76	1.73	− 14	2.0
June 23	16 10	67.4	.81	0.005	0.414	2.12	.....	.....	....
	16 58	64.6	.88	0.005	0.367	2.07	.....	.....	....
	17 32	63.8	.96	0.005	0.356	2.20	2.13	− 3	1.8
Corona on June 8.....	11 18	53.3	0.60	.....	0.252	.....	1.07	.....	1.8

Ratio of corona to full moon, 0.50

The first three nights in Table III are included only as a general check upon the measures at full moon. The correction for atmospheric absorption, which increases the values as much as five-fold, shows that it is useless to measure the moon at low altitudes unless a star near by can be used for comparison. The measures

of the full moon on June 23 were quite satisfactory, and the sky was estimated to be fully as good as at the time of the eclipse. The application of the absorption correction changes the ratio corona to moon from about 0.6 to 0.50, and it is evident that no great error has been introduced here by improper allowance for the atmosphere.

The method of allowing for the atmospheric absorption in our photometric work on stars at this observatory is to take the reduction to zenith from Müller's[1] table and multiply by an arbitrary factor, based upon the observer's judgment, but this factor is often determined by measures of suitably placed stars, and with constant instrumental conditions is fixed by the absolute amount of photo-electric effect produced by any star which has been observed on many nights. If the reduction to outside the atmosphere is desired, an additional allowance of 0.20 magnitude times the factor is made. Since for a potassium cell our usual factor for a good night is 1.8, this gives 0.36 magnitude as the absorption at the zenith. For the work on stars, where the correction is always a differential one, it is not a great matter if the absolute value of the assumed absorption is considerably in error, as no theory can allow for the sudden and irregular changes in the transparency of the air at any ordinary station. There is of course a great difference in the absorption for light of different wave-lengths, but the foregoing estimate is considered to be about right for the integrated effect with a potassium cell. Although it is quite unsatisfactory to guess in this way at the effect of our atmosphere on the brightness of the corona, it is better than to ignore the effect altogether, as has been done in most cases.

We give in Table IV other photometric measures of the corona subsequent to 1870 and 1878, when only first rude attempts were made.

The photo-electric value ought to be fairly comparable with the photographic results, considering the color-curve of the potassium cell. Our result does fit in between the extremes, but it is evident that there are large outstanding differences between observers which are probably not due to changes in the corona.

[1] *Photometrie der Gestirne*, p. 515.

The values ascribed to Pickering and Holden are not given explicitly in their papers but may be derived from their data, using Pickering's figure for the moon for both cases.

The photographic results by Turner apparently depend upon a value of 0.02 foot-candles for the moon, which is all right for visual light, but, we suspect, may be five or ten times too small for the moon's photographic effect. If this surmise is correct, then Turner's values should be considerably reduced.

The volumes of the British Astronomical Association, edited by Maunder, are not available to us, and we are indebted to Mr. Parkhurst for the reference to them. We are quite at a loss to account for the high values obtained in 1898 and 1900.

The independent measures of Graff and Schwarzschild in 1905 seem to be in good agreement.

Perrine states that most of the light which goes into his value of 0.11 is additional to what is shown on an ordinary photograph, as he allows for the part of the corona which is hidden by the moon. He considers that most of the coronal light comes from the inner ring about the sun's limb, only 1 minute of arc in apparent width.

Of the visual determinations, those published by Abney and Thorpe were made with the same instrument, the observers being Douglas in 1886 and Forbes in 1893. A direct comparison with the moon was not made, and the corona was expressed in Siemens' units at 1 foot, 0.0197 in 1886 and 0.026 in 1893, the conditions being poor at the first date. Following Turner's discussion of these measures, the values in terms of the full moon are 0.8 and 1.1 respectively, which are inserted in Table IV.

Leuschner in 1889 found 0.0086 units of a wax candle at 1 foot. We arbitrarily assume the moon to be 0.02 in the same unit, and derive 0.4 moon for the corona.

The results of Fabry and Knopf are as given in the originals.

As far as we can make out, all of the photographic determinations are for the corona exclusive of the sky background. The values of Abney and Thorpe apparently include the sky, an area of perhaps 12° diameter according to Turner. The results of Leuschner in 1889 exclude the sky, and the same is presumably

true of the careful measure of Fabry in 1905, while Knopf included the background in the immediate vicinity of the corona.

There are large outstanding corrections for atmospheric absorption which should be applied to the results in Table IV to make

TABLE IV

TOTAL LIGHT OF THE CORONA

ECLIPSE	OBSERVER	IN TERMS OF FULL MOON	REFERENCE
	Photographic Determinations		
1886	W. H. Pickering	0.025	*Harvard Annals*, **18**, 104, 1890
1889 (January)	Holden	0.04	*Lick Contributions*, **1**, 14, 1889
1889 (December)	Holden	0.02	*Ibid.*, **2**, 14, 1891
1893	Turner	0.6	*Proc. Roy. Soc.*, **68**, 36, 1901
1898	Turner	1.1	*Ibid.*
1898	Bacon and Gare	2.7	*The Indian Eclipse of 1898* (E. Walter Maunder, ed.), p. 129
1900	Gare and Johnston	10.(?)*	*The Total Solar Eclipse of 1900* (E. Walter Maunder, ed.), p. 154
1905	Graff	0.26	*Hamburger Abhandlungen*, **3**, 48, 1913
1905	Schwarzschild	0.17	*Astronomische Mitteilungen*, Göttingen, No. 13, p. 36
1908	Perrine	0.11	*Lick Obs. Bull.*, **5**, 98, 1909
	Visual Determinations		
1886	Abney and Thorpe	0.8	*Phil. Trans.*, **108A**, 363, 1889
1889 (January)	Leuschner	0.4	*Lick Contributions*, **1**, 100, 1889
1893	Abney and Thorpe	1.1	*Phil. Trans.*, **187A**, 433, 1896
1905	Fabry	0.75	*Comptes rendus*, **141**, 870, 1905
1905	Knopf	0.85	*Hamburger Abhandlungen*, **3**, 80, 1913
	Photo-Electric Determination		
1918	Kunz and Stebbins	0.50	This paper

* Measured as 6 c.p.

them homogeneous, but we have not the data at hand to hazard such a procedure. In a general way it is evident that the visual values run about ten times larger than the photographic, except for the British observers ,and the photo-electric result lies between, but nearer the visual.

The question naturally arises as to how much of the total light which we assume to be from the corona in 1918 was due to the prominences, which were unusually bright at this eclipse. The short-exposure photographs show the prominences to be intrinsically more intense than adjacent regions of the inner corona, and can it be that what we measured was the prominences and not the corona at all? The answer is that in the photographic spectrum of the prominences the most prominent features are the H and K calcium lines, which have almost no effect upon the photo-electric cell. From a print of the spectrum obtained at Green River and kindly sent to us by Mr. Parkhurst, it is seen that the prominence radiations which would affect the cell are principally $H\beta$ and $H\gamma$; but it seems that the selective effect of cutting out the H and K light, combined with the long stretch of continuous coronal spectrum to which the cell is sensitive, would make the prominences much less effective on the cell than on the photographs. It is possible that a study of the 1918 plates will give a measure of the photographic light of the prominences as compared with the corona, but until this is accomplished we cannot give a numerical estimate of the effect of the prominences.

SUMMARY

By means of a potassium photo-electric cell the corona of June 8, 1918, was compared with a standard candle, two electric lamps, the full moon, and with an area of sky during totality and in full sunshine. The numerical results are as follows:

Observed total light of corona	0.60 candle-meters
Same, corrected to outside atmosphere	1.07 candle-meters
Observed ratio of corona to full moon	0.6
Same corrected to outside atmosphere	0.50
Observed ratio of corona to sky circle $\frac{1}{2}°$ diameter 8° from uneclipsed sun	0.105
Same during totality	640.
Ratio of intensity of daylight sky 8° from sun to intensity of same area during totality	6100

All of the foregoing measures refer to the light to which the photo-electric cell is sensitive (see Fig. 2). It is probable that the light

from the prominences had a small effect upon the measures, which, however, can be evaluated from the photographs.

We are indebted to Dean David Kinley for a grant from research funds of the Graduate School which made the expedition possible; also to Dr. Elmer Dershem, instructor in astronomy, and to Mr. J. B. Hayes, mechanician in the department of physics, for efficient assistance in the preparations for the eclipse. We are also glad to record that the work here described was supported in part by a grant from the Draper Fund of the National Academy of Sciences.

UNIVERSITY OF ILLINOIS
January 1919

THE MAGNETIC POLARITY OF SUN-SPOTS[1]

By GEORGE E. HALE, FERDINAND ELLERMAN,
S. B. NICHOLSON, AND A. H. JOY

Whirling storms in the earth's atmosphere, whether cyclones or tornadoes, follow a well-known law which is said to have no exceptions: the direction of whirl in the Northern Hemisphere is left-handed or counterclockwise, while in the Southern Hemisphere it is right-handed or clockwise. The theory of terrestrial cyclones is still very obscure, but the direction of whirl is evidently determined by the increase in linear velocity of the air from pole to equator, due to the earth's rotation. The question naturally arises whether storms in the solar atmosphere are also whirlwinds, and, if so, what law governs their direction of whirl in the Northern and Southern hemispheres.

The first definite evidence bearing on this question was obtained with the spectroheliograph in 1908.[2] Photographs of the hydrogen flocculi made with the Hα line showed clearly marked vortical structure in regions centering in sun-spots. This structure was found to be repeated in hundreds of spots, leaving no doubt as to the generality of the phenomenon. Furthermore, photographs were obtained showing masses of hydrogen in the act of being drawn from a great distance toward the center of sun-spots, as though sucked into a vortex.

These photographs suggested the hypothesis that a sun-spot is a vortex, in which electrified particles, produced by ionization in the solar atmosphere, are whirled at high velocity. This might give rise to magnetic fields in sun-spots, regarded as electric vortices. A search for the Zeeman effect led to its immediate detection, and abundant proofs were soon found of the existence of a magnetic field in every sun-spot observed.[3]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 165.

[2] Hale, "Solar Vortices," *Mt. Wilson Contr.*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Hale, "On the Probable Existence of a Magnetic Field in Sun-Spots," *Mt. Wilson Contr.*, No. 30; *Astrophysical Journal*, **28**, 315, 1908.

Subsequent investigations have led to the view that two classes of vortices are involved:

1. High-level hydrogen vortices, centering in sun-spots, which are revealed by the spectroheliograph when monochromatic images of the sun are photographed with the light of the central part of the Hα line. In these vortices, which sometimes cover vast areas of the solar surface, the motion of the hydrogen appears to be spirally inward and downward. Little is known, except by inference, as to the form of the stream-lines in the lower levels close to the photosphere. There is reason to infer, however, that the hydrogen gas, descending toward the solar surface, moves spirally outward in the lower chromosphere above the spots.[1]

2. Low-level electric vortices, formed in the photosphere, which constitute the sun-spots themselves. In these vortices the motion of the gases appears to be spirally upward from within the photosphere and outward along its surface.[2] It is easy to show by laboratory experiments that such a primary vortex formed in water may set up a secondary vortex in a gaseous atmosphere above it, closely analogous to the hydrogen vortices above sun-spots.

The present paper deals with the magnetic polarity of sun-spots, though some reference will also be made to the closely related phenomena exhibited by the vortex structure of the hydrogen flocculi. The purpose in view is to discover the law of magnetic polarities, if such exists, and to consider whether this law is subject to variation in the course of the sun-spot cycle. Subsequent papers will deal with the various magnetic peculiarities of sun-spots and the structure of the hydrogen flocculi, with special reference to the nature of the vortices associated with sun-spots.

METHOD OF OBSERVATION

It is a well-known fact that when a normal Zeeman triplet is observed along the lines of force of a magnetic field the central (p) component is absent and the two side (n) components are circularly polarized in opposite directions. A quarter-wave plate and Nicol

[1] St. John, *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 322, 1913; Evershed, *Kodaikanal Observatory Bulletin*, No. 15; Memoirs, **1**, Pt. 1, 1909.

[2] St. John, *loc. cit.*

prism mounted over the slit of the spectroscope permit either *n*-component to be cut off at will by rotating the Nicol. Furthermore, if the polarizing apparatus be adjusted so as to extinguish one component, reversal of the current through the coils of the magnet will cause this component to reappear, while the other will be extinguished. The method thus offers a simple means of determining the polarity of a magnetic field, which can still be used when the angle between the line of sight and the lines of force is as great as sixty or seventy degrees. In this case, however, the *p*-component of the triplet is present, and the elliptically polarized light of the *n*-components can be only partially extinguished.

This method is employed daily for the study of the magnetic polarity of sun-spots with the aid of the 75-foot spectrograph of the 150-foot tower telescope on Mount Wilson. A 12-inch (30.5 cm) visual objective of 150 feet focal length, mounted just below the second mirror of the coelostat near the summit of the tower, produces at the base of the tower an image of the sun about 43 cm in diameter, any portion of which may be brought upon the slit of the spectrograph below by means of the electric motors that control the slow motions of the coelostat and second mirror. The massive circular head of the spectrograph, which carries the slit in a horizontal plane, can be rotated to any desired position angle. After passing through the slit, the light from the sun-spot, or other portion of the solar image, descends vertically into a subterranean well, 10 feet (3.0 m) in diameter, with concrete walls. The collimating lens of 6-inch (152 mm) aperture is 75 feet (22.9 m) below the slit. This lens and the large Michelson grating below it are mounted on a heavy support at the bottom of the well, where the temperature is essentially constant throughout the year. After falling on the grating, the light is returned through the collimating lens, which forms an image of the spectrum at a point near the slit of the spectrograph. Here it can be observed visually, or photographed if desired. There is no connection (other than the walls of the well) between the head of the spectrograph, which carries the slit, and the support for the collimator-camera lens and grating at the bottom of the well. When the slit is rotated in position angle, the grating support is rotated through the same angle by means of

an electric motor, thus bringing the lines of the grating again into parallelism with the slit. All of the necessary adjustments, including the rotation of the dome at the summit of the tower, the slow motions of the coelostat and second mirror, the focusing of the sun's image on the slit, the focusing of the collimator-camera lens, the inclination of the grating to bring different orders of spectra into view, and the rotation in azimuth of the grating support, are accomplished by electric motors controlled by push buttons near the hand of the observer.

Most of the observations, both visual and photographic, of the Zeeman effect in sun-spots are made in the second-order spectrum, where the linear dispersion at the region in question is 1 A = 2.96 mm. For the daily determination of spot polarities the sharp iron triplet λ 6173.553 is usually employed.

In work of this nature, as already stated, it is necessary to use a Nicol prism, which is supported just over the slit of the spectrograph, and surmounted by a compound quarter-wave plate, so constructed that the principal sections of the successive mica strips (2 mm wide) are normal to one another. The Nicol prism, 130 mm in length, 18 mm high, and 10 mm wide (effective width 5 mm), was built by Werlein (from four sections each 32.5 mm long) for use with the 75-foot spectrograph (see Plate III*a*, *Contribution* No. 71). The compound quarter-wave plate, there shown swung to one side, can be turned into position above the Nicol. In view of the considerable focal length of the spectrograph, the distance of the quarter-wave plate from the slit (65 mm) is not sufficient to reduce materially the sharpness of the dividing lines between adjoining strips of spectra. For the study of plane polarization phenomena, a compound half-wave plate is substitued for the compound quarter-wave plate. Circular half-wave and quarter-wave plates, mounted so that they can be rotated in position angle, are also used for special purposes.

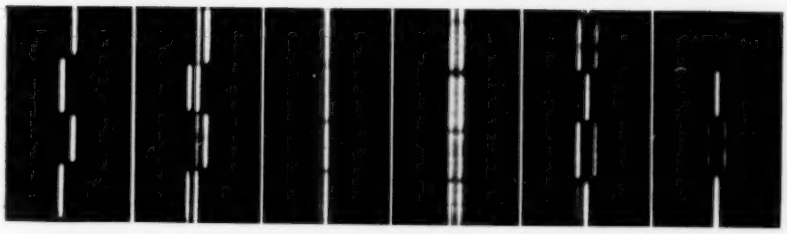
With this apparatus the magnetic polarities and the strength of the magnetic field in all sun-spots are recorded daily (see Fig. 1). A sheet of paper is placed in the focal plane of the telescope and all spots visible are traced in outline upon it. The polarity of each spot is then indicated by a "V" or an "R," according as the violet

FIG 1.—Reproduction of sketch showing daily record of observations of sun-spot polarities

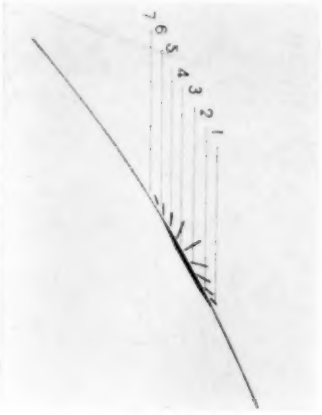
or red component of the Zeeman triplet is transmitted by a given strip of the quarter-wave plate. As the diameter of the focal image of the sun is 43 cm, it is possible in this way to observe very small spots. In addition to the record of polarities, the strength of the field in each spot is measured by means of a parallel-plate micrometer. The scale of this micrometer has been carefully calibrated by Ellerman and Nicholson, and when used to measure a triplet whose separation for a given field-strength has been determined in the laboratory its readings are readily convertible into gausses. In the case of the sharp triplet λ 6173, the *n*-components may still be distinguished separately in sun-spots when the field-strength is as low as 1000 gausses. For greater field-strengths the observed values are therefore fairly reliable, but below this limit they must be regarded as merely approximate. The readings with the parallel-plate micrometer are recorded in degrees; and since for λ 6173 one degree corresponds approximately to 100 gausses, the designation "R 28" (see Fig. 2) at a certain point on a sun-spot indicates that the polarity at this point corresponds to that of the north magnetic pole of the earth, and that the field-strength is about 2800 gausses. "V 7" would mean that the polarity corresponds to that of the south magnetic pole of the earth, while the field-strength is of the order of 700 gausses.

THE DETERMINATION OF SUN-SPOT POLARITIES; INCLINATION OF THE LINES OF FORCE

The determination of the magnetic polarity of a sun-spot depends upon an estimate of the relative intensities of the red and violet components of a Zeeman triplet. The zinc triplet λ 4680 in the spectrum of a spark between the poles of a large Weiss magnet, when photographed with a Nicol prism and compound quarter-wave plate at angles of 0°, 60°, and 90° with the lines of force, presents the appearance shown in Plate V*a*, *b*, and *c*. When the observation is made parallel to the lines of force, the *p*-component of the triplet is absent and one of the *n*-components is completely cut off. At right angles to the lines of force the *p*-component is twice as strong as the *n*-components (in the case of a normal triplet), while the two *n*-components are of equal intensity. At intermediate



a *b* *c* *d* *e* *f*



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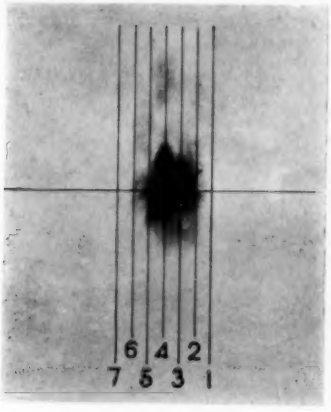

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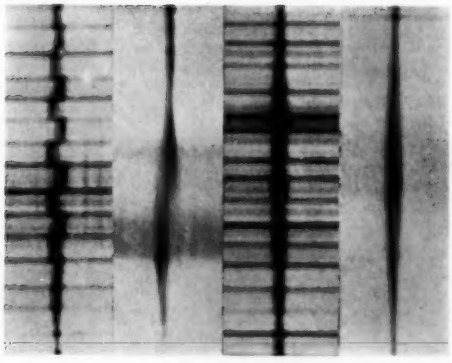


i *j* *k* *l*

a, *b*, *c*, Observations of the zinc triplet λ4680 in the physical laboratory, with compound quarter-wave plate in front of the slit of the spectrograph; inclinations of line of sight to lines of force are 0°, 60°, 90°, respectively; *d*, *e*, *f*, the same, with compound half-wave plate substituted for the quarter-wave plate; compare with Fig. 3 and *i* and *k* of this plate.

g, Lines of force in a sun-spot near the west limb on October 1, 1915; *h*, photograph of the same spot; the numbered lines indicate successive positions of the slit of the spectrograph used to determine the inclination of the lines of force.

i, *j*, *k*, *l*, Iron triplet λ 6173 photographed in spectra of various sun-spots; *i*, *j*, circularly polarized light, spot near center of sun, observed with Nicol and (*i*, compound; *j*, single) quarter-wave plate; *k*, *l*, plane polarized light, spot near limb, with Nicol and (*k*, compound; *l*, single) half-wave plate; *j* shows reversal of polarity in two adjacent umbrae of large spot-group of August, 1917.

angles the plane polarized p-component is of intermediate intensity, while the elliptically polarized n-components are no longer completely cut off by the Nicol prism and quarter-wave plate. The relative intensities of the three components of a normal triplet for

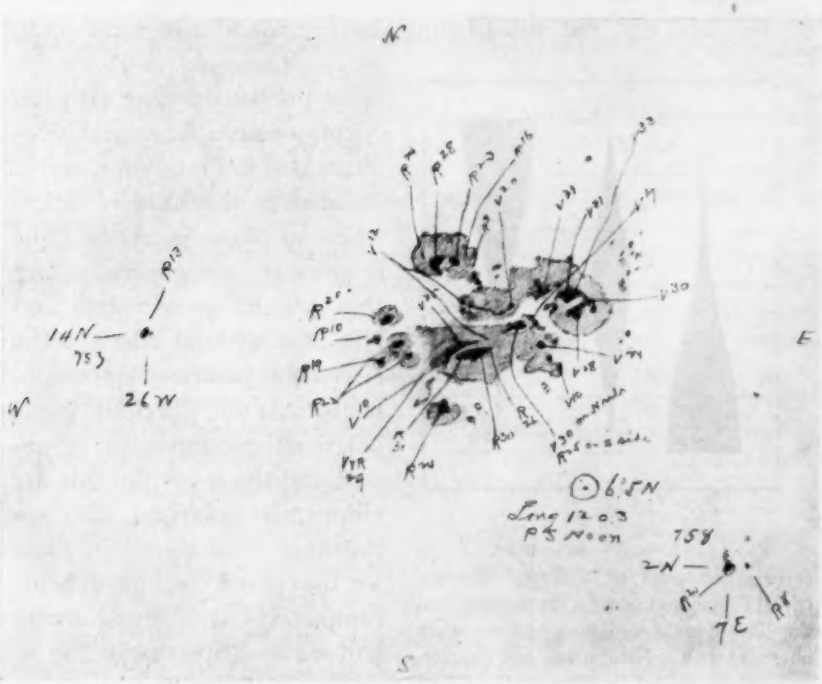


FIG. 2.—Sketch of large sun-spot group from the daily record for August 10, 1917, showing the manner of indicating the polarity and field-strength at different points in the group.

one set of alternate strips, when observed at any angle from 0° to 180° with the lines of force, are given by

$$n_V=\tfrac{1}{4}(1-\cos\gamma)^2 \quad p=\tfrac{1}{2}\sin^2\gamma \quad n_R=\tfrac{1}{4}(1+\cos\gamma)^2$$

where n_V, p, and n_R are the intensities of the violet, central, and red components respectively; γ is the angle between the line of sight and the lines of force, and the unit of intensity is such that $1=n_V+p+n_R$.[1] The variation of intensity in the three components with

[1] Seares, *Mt. Wilson Contr.*, No. 72, p. 5; *Astrophysical Journal*, **38**, 99, 1913.

the angle γ is illustrated by Fig. 3. We thus have a means of determining the angle between the line of sight and the lines of force in observations of sun-spots. The important bearing of this on polarity determinations will shortly appear.

Repeating the foregoing observations, at the same angles of 0°, 60°, and 90°, but substituting the compound half-wave plate for the compound quarter-wave plate previously used with the Nicol, we have the appearances illustrated in Plate V*d*, *e*, and *f*. Parallel to the lines of force, when no plane polarized light is present, we naturally find that the half-wave plate and Nicol are without effect on the circularly polarized *n*-components. At 60°, where the plane polarized *p*-component is absent and the *n*-components are elliptically polarized, the appearance is as shown in Plate V*e*, the central component being completely cut off by alternate half-wave strips, while the *n*-components are materially reduced in intensity.

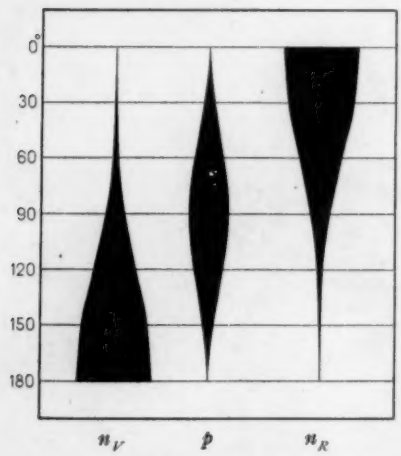


FIG. 3.—Relative intensities of the three components of a normal Zeeman triplet for inclinations of 0° to 180° between the line of sight and lines of force when observed with a Nicol prism and quarter-wave plate placed in front of the slit of the spectrograph. Thus for 0° the relative intensities are 0, 0, 1, respectively; for 90°: 0.25, 0.50, 0.25; for 180°: 1, 0, 0.

Consider now the bearing of these observations on the determination of the polarity of a sun-spot when close to the sun's limb. Let us assume that the lines of force at the center of the spot are parallel to a radius from the sun's center passing through this point, and that at other parts of the umbra and penumbra the lines of force are inclined approximately as indicated in Plate V*g*. This drawing relates to a spot photographed near the west limb of the sun on October 1, 1915, and reproduced in Plate *Vh*, where the scale is that of the image of the sun at the focus of the 150-foot tower telescope. The triplets λ 6302.709 and λ 6301.718 were observed

at various parts of the spot, the successive positions of the slit on the image of the spot being indicated on the illustrations by the lines numbered 1 to 7. The observations were made visually by Hale in the second-order spectrum of the 75-foot spectrograph, using the Nicol and the compound quarter-wave plate over the slit. As these observations are typical of all fairly symmetrical spots when near the sun's limb, the phenomena observed at each position of the slit may be indicated here. Reference is made to the appearance of the triplet λ 6173.

1. Slight "zigzag" effect, red *n*-component (R) stronger than violet *n*-component (V). Diffuse.

2. Widened, diffuse. R stronger than V. Sharp at one point in spot, where *p* and R are separated. R stronger than *p*. V absent or very faint.

3. Wide, diffuse. R stronger than V. Three components of triplet sometimes visible.

Between (3) and (4). *p* visible but faint. V strong and separated from *p*. R apparently absent.

4. More diffuse. *p* hardly separated from V, which is very strong Marked "zigzag."

5. Similar, but less "zigzag." Diffuse.

The chief point to be noticed is that, whereas the red *n*-component (R) was the stronger on the side of the spot toward the limb, the violet *n*-component (V) was the stronger on the opposite side of the spot. In other words, opposite polarities were indicated by the observations on the opposite sides of the spot. This is easily explained when the inclination of the lines of force at various points in the spot is considered.

As already stated, Plate V*h* represents the spot at the point of observation near the west limb of the sun. The direction of the lines of force corresponding to the various parts of the spot is hypothetically indicated in Plate V*g*. Thus when the slit occupied positions (2) and (3) the lines of force were directed away from the observer, and *R* was stronger than *V*.[1] Between (3) and (4) the *n*-components became of equal intensity, indicating that the line of sight was nearly at right angles to the lines of force. In subsequent positions of the slit the violet *n*-component, which had been

[1] Assuming the lines of force at the center of the spot to be directed radially outward from the sun's center.

weaker than the red component in positions (2) and (3), was invariably the stronger, showing that the lines of force from the inner side of the spot were directed toward the observer. Thus the true polarity of a sun-spot, corresponding with that given by observations made on the umbra when the spot is near the center of the sun, may also be determined near the limb by observing that portion of the penumbra which lies toward the center of the sun.

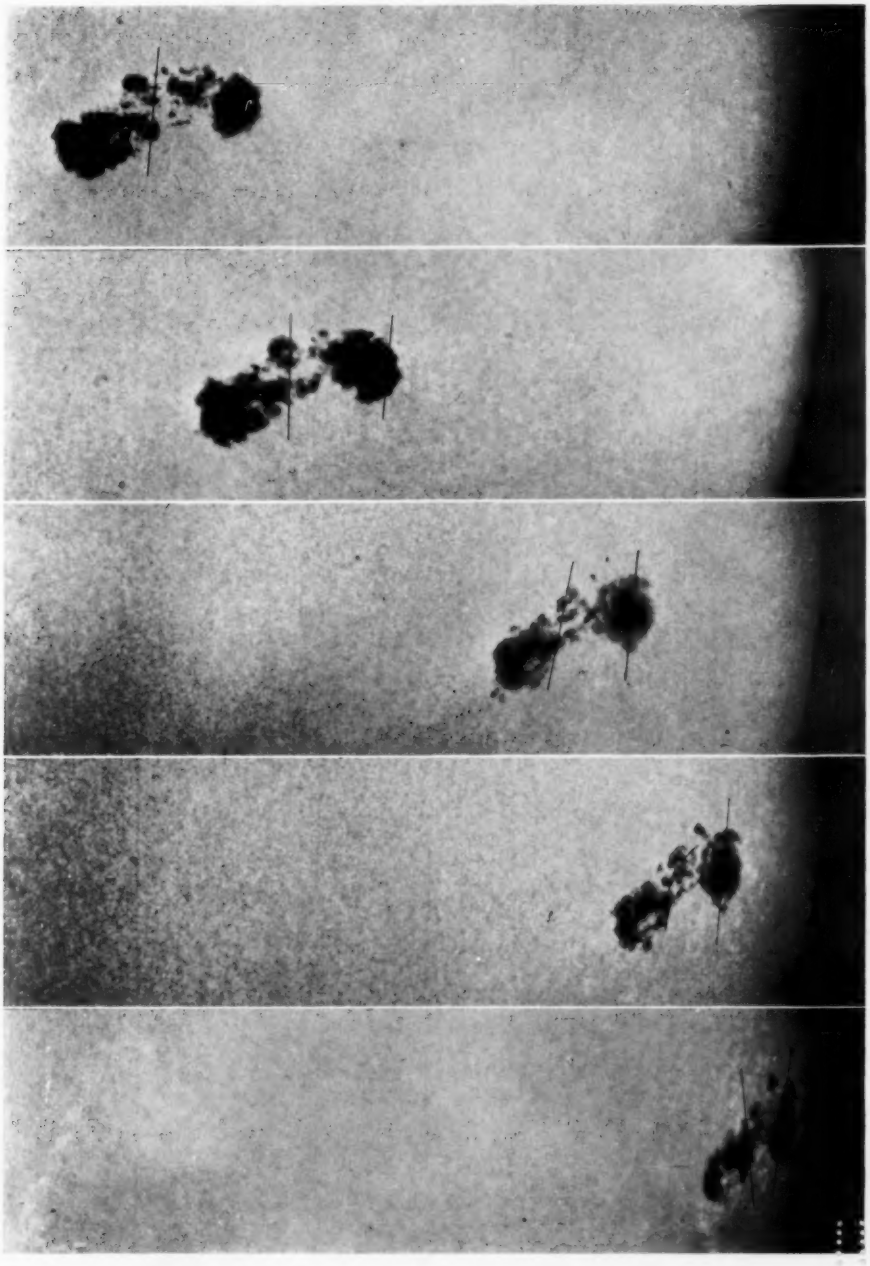
The observations indicate that at some position of the slit between (3) and (4) the lines of force were nearly at right angles to the line of sight. At this point the compound half-wave plate gave strong evidence of plane polarization (Plate V*k*), while the the quarter-wave plate indicated the same result by showing that maximum intensity shifted from *R* to *V*.

The position on the spot occupied by the slit when the red and violet components of a Zeeman triplet are of equal intensity may be called the "neutral line" (see Fig. 3). By determining the position of this line in a large number of spots we may obtain data which will enable us to fix, with some precision, the average inclination of the lines of force in a plane passing through the center of the sun and the line of sight.

The photographs of a large bipolar spot group made on February 9, 10, 12, 13, 14, 1917, and reproduced in Plate VI, will serve to illustrate how the position of the neutral line changes with the longitude. Observations were made on both of the principal spots as the group was carried by the solar rotation toward the west limb from a point near the center of the sun. One day's observations are missing, because of clouds. The gradual displacement with longitude of the neutral line illustrated by these observations is perfectly typical, and may be seen in any spot of sufficient size as it is carried by the solar rotation away from the eastern or toward the western limb.

Irregularities in the form of spots, the presence of small components opposite in polarity to the chief umbra, and other magnetic peculiarities such as are noted below, frequently complicate the observations and affect the form and position of the neutral line. But its average shift with longitude, determined from observations of a considerable number of spots, gives the approximate inclination of the lines of force in various parts of the umbra and

PLATE VI



PHOTOGRAPHS OF LARGE BIPOLAR SUN-SPOT GROUP

a, February 9; *b*, February 10; *c*, February 12; *d*, February 13; *e*, February 14. 1917, showing change in position of the neutral line with change in longitude of spot.

penumbra. Thus we find, from 105 observations of 61 spots made by Joy and Nicholson, the positions of the neutral line and the corresponding inclination of the lines of force (taken as normal to the lines of sight passing through the neutral line) given in Table I.

The position of the neutral line is given in tenths of the spot's radius, measured from the center of the spot toward the limb. In the average spot of moderate size the radius of the umbra is 0.4 that of the penumbra.

TABLE I

INCLINATION OF LINES OF FORCE

Longitude	Position of Neutral Line	Angle Between Lines of Force and Solar Radius
30°–40°	8.0	55°
40 –50	7.0	45
50 –60	4.7	35
60 –70	3.2	25
70 –90	2.0	10

These results relate to the lines of force that lie in a plane passing through the center of the spot, the center of the sun, and the line of sight. They do not show, however, the inclination of the lines of force in the plane at right angles. These can be very accurately determined by a method first applied by Nicholson, as follows:

When light from a Zeeman triplet is examined in a direction normal to the lines of force the vibrations producing the *p*-component are parallel to the lines of force. When a sun-spot is observed near the sun's limb the lines of force lying in a meridional plane through the center of the spot are nearly normal to the line of sight, and their inclination to the north or south can be found by determining the direction in which the light of the *p*-component is vibrating. The simplest way to do this would be to pass the light through a Nicol and observe in what part of the spot the *p*-component is completely extinguished for a given position of the Nicol. For that region the lines of force would be parallel to the long diagonal. A modification of this method has been used because the grating over the 75-foot spectrograph almost completely plane-polarizes the

light in the region generally observed, with the result that for certain positions of the Nicol it would be almost completely extinguished. The difficulty could be avoided by leaving the Nicol fixed with reference to the slit and rotating the whole spectrograph. In practice the same result is accomplished by using a half-wave plate placed over a fixed Nicol. The half-wave plate is mounted on a scale calibrated in degrees so that the angle between its principal axis and that of the Nicol can be observed. By observing this angle the direction of vibration of the *p*-component projected on a plane perpendicular to the line of sight can be determined in all parts of the spot. Since the plane through the sun's axis and the center of the spot is nearly perpendicular to the line of sight, observations of points in the spot lying in the plane give directly, with good approximation, the inclination of the lines of force toward the north or south. The results of 24 observations by Nicholson on three typical unipolar spots are as follows, the unit of distance, as before, being one-tenth of the radius of the spot.

Distance from Center of Spot	Angle Between Lines of Force and Solar Radius
0	0°
3	18
6	49
9	73

The inclinations found by the two methods are shown in Fig. 4, where the ordinates are angles between the lines of force and the solar radius and the abscissae are distances from the center of the spot. The results of the first method are indicated by crosses and of the second by circles. Considering the difficulties and uncertainties of observation, the agreement is excellent.

Additional information can be obtained by determining the relative intensities of the *n*- and *p*-components of a Zeeman triplet in different parts of a spot observed near the center of the sun. The results of such observations vary among themselves, but in many spots the *p*-component is strong even at the center of the umbra when the spot is near the center of the sun (see Plate V*i*, *j*). This investigation, the results of which are not essential in the present study of polarities, is being continued by Nicholson.

By taking into account the position of the neutral line and avoiding the observation of spots at the extreme limb of the sun (where the lines of force along the line of sight are frequently not visible at the outer edge of the spot), the polarities of sun-spots may be determined with certainty. It is to be understood that for this purpose a quarter-wave plate is always used with a Nicol prism over the slit of the spectroscope. Serious errors in the determination of the relative intensities of the lines of spot triplets

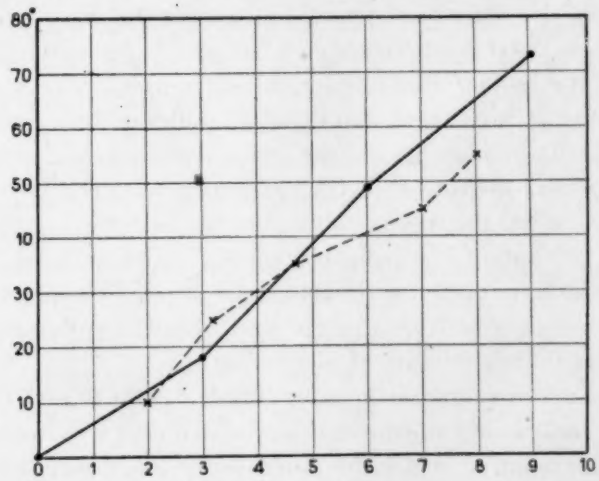


FIG. 4.—Inclination (ordinates) of lines of force to sun's radius at different distances from the center (abscissae, in tenths of radius of spot) of sun-spots. Crosses indicate results from observations of the position of the neutral line. Points are from measures of the orientation of the plane of polarization for the *p*-components in spots observed near the sun's limb.

may enter, as Zeeman has pointed out, when the observations are made without polarizing apparatus. In the case of the 75-foot spectrograph, for example, the plane polarization due to the grating varies greatly for different wave-lengths and for different orders of the spectrum. It is therefore entirely insufficient to determine the relative intensities of the lines without complete knowledge of the polarization phenomena of the grating and also those of the tower telescope. With a Nicol and quarter-wave plate, however, the results of polarity observations are essentially unaffected by these causes.

BIPOLAR SUN-SPOTS

In Hale's first paper "On the Probable Existence of a Magnetic Field in Sun-Spots,"[1] photographs were reproduced of two large spots, of opposite polarity, lying on opposite sides of the solar equator. Other cases which at first seemed to suggest a relationship between polarity and hemisphere were subsequently found. But it soon appeared that the simple law of terrestrial cyclones does not apply to the sun; for spots of opposite polarity were detected, not only in the same hemisphere, but also in the same spot-group.

Thus the large spot (Greenwich No. 6728) observed in the focal image of the 60-foot tower telescope on September 24, 1908, was seen to have at least three well-defined smaller umbrae, in addition to the principal umbra, within the boundary of the large penumbra. Photographs of the iron triplet λ 6303, made with the 30-foot spectrograph, showed the three small umbrae to have the same polarity, opposite to that of the principal umbra and penumbra. Many similar cases have been found, while cases of small companion spots, completely separated from a larger member of the group, and differing from it in polarity, are also common.

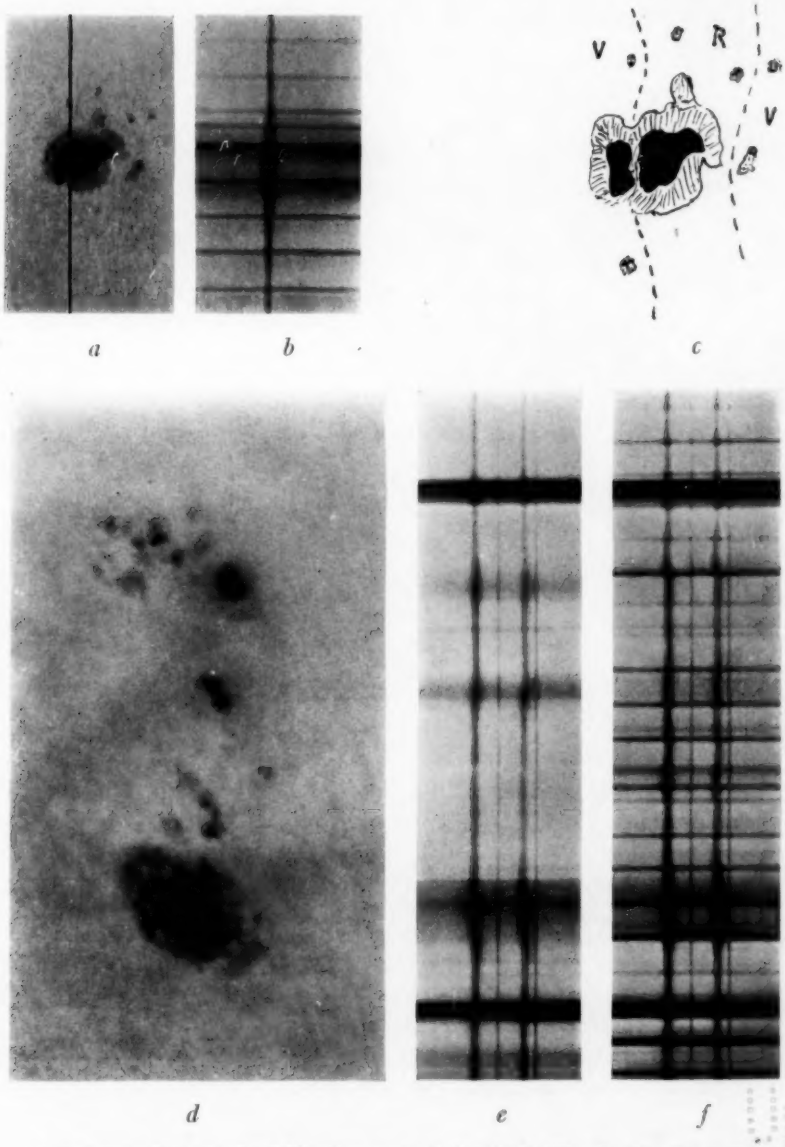
In one very remarkable instance, illustrated in Plate VII*a* and *b*, two large umbrae of the same spot, separated only by a bridge, were of opposite polarity, while the polarities of other members of the same group were as indicated in the sketch, Plate VII*c*, accompanying the photograph.

It fortunately happens, however, that cases of mixed polarity are not so common as to obscure our perception of a simple unifying principle leading directly to the detection of a general law of polarities. This has its origin in a well-known peculiarity of sun-spots, indicated in the records of the earliest observers, and commented upon by Carrington.

Sun-spots frequently occur in pairs, the principal members of which may be several degrees apart. The western or preceding member of such a group is often the first to be formed, but sooner or later a second spot, comparable with the first in size, but frequently smaller, or split into several components, is likely to appear behind it. Sometimes both members of the group appear simul-

[1] *Mt. Wilson Contr.*, No. 30; *Astrophysical Journal*, **28**, 315, 1908.

PLATE VII



a *b* *c*

d *e* *f*

a, Sun-spot photographed March 9, 1916, in longitude W. 23°, the umbra divided by a bridge; *b*, iron triplet λ6173 observed with Nicol and compound quarter-wave plate, the slit occupying the position shown by the line in *a;* the nearly equal intensities of the *n*-components in the *same* strip of spectrum indicate the presence of two fields of opposite polarities; compare with Plate IV*i*, which shows the appearance when only a single field is present; *c*, sketch showing the distribution of polarities for other members of the group.

d, Bipolar sun-spot group photographed June 19, 1914; *e*, *f*, the iron lines λ 6301.7 and λ6302.7 as shown in the spectra of the three principal members of the group, with Nicol and (*e*, single; *f*, compound) quarter-wave plate; the configuration of the lines indicates that the two smaller spots are of the same polarity, but opposite to that of the largest spot.

taneously, and in other cases the following member is formed first. Many minor spots usually accompany the larger ones, either clustered about them or lying in the space between the principal spots. It is probably a significant fact that the axis of the group usually makes only a small angle with the equator.

TABLE II

INCLINATION OF AXIS OF SUN-SPOT GROUPS

Semicycle	Latitude						
	0°–4°	5°–9°	10°–14°	15°–19°	20°–24°	25°–29°	30°–34°
Min.–Max. 1856–1860.....	7°(3)*	5°(27)	10°(69)	7°(94)	9°(103)	8°(60)	13°(20)
Max.–Min. 1860–1867.....	1 (24)	3 (117)	4 (148)	6 (73)	9 (40)	8 (9)	14 (3)
Min.–Max. 1867–1871.....	4 (4)	5 (15)	5 (55)	6 (80)	6 (97)	9 (45)	8 (23)
Max.–Min. 1871–1879.....	7 (35)	3 (139)	6 (147)	6 (90)	8 (65)	10 (13)	10 (13)
Min.–Max. 1879–1884.....	7 (11)	2 (42)	4 (105)	3 (123)	9 (85)	9 (31)	14 (9)
Max.–Min. 1885–1889.....	3 (34)	−1 (72)	6 (110)	7 (43)	10 (7)	17 (2)	(0)
Min.–Max. 1889–1893.....	−2 (7)	0 (21)	6 (81)	6 (93)	10 (88)	10 (46)	10 (12)
Weighted mean inclination and number of spots	3.7 (118)	2.4 (433)	5.6 (715)	5.8 (596)	8.7 (485)	9.3 (206)	10.8 (80)

* Quantities in parenthesis are numbers of spots.

A study by Joy of the sun-spot drawings of Carrington (1856–1861)[1] and Spörer (1861–1893)[2] shows that there is little change in this angle during the life of the group, but that in the mean the angle bears a definite relation to the latitude of the group. Twenty-six hundred and thirty-three bipolar and multiple groups, covering three and one-half sun-spot cycles, were examined. The following spot of the pair tends to appear farther from the equator than the preceding spot, and the higher the latitude, the greater is the inclination of the axis to the equator. This relation holds for both hemispheres. The details are shown in Table II and the results are illustrated in Fig. 5.

[1] *Observations of Spots on the Sun*, London, 1863.

[2] *Publicationender Astronomischen Gesellschaft*, 13; *Pub. Astrophys. Obs. zu Potsdam*, No. 1, 1878; No. 5, 1880; No. 17, 1886; No. 32, 1894.

In general, the angle of inclination was found to depend entirely on the latitude of the group, without reference to the number of the cycle or the time within the cycle. A knowledge of the polarities of the spots would have aided greatly in determining the position of the axes of the groups.

The most significant characteristic of these binary spot-groups lies in the fact that the two principal members, whether single or multiple, are almost invariably of opposite magnetic polarity. A photograph made in the second-order spectrum of the 75-foot spectrograph will serve to illustrate this point, and at the same time to indicate how these polarity phenomena may be recorded photographically. The long Nicol prism and compound quarter-wave plate are used over the slit and the spectrograph is rotated in position angle until the slit passes through the two principal members of the group. A single exposure on a wide Zeeman triplet such as λ 6173 or λ 6303 then gives the polarity of the two members, as shown in Plate VII. The spot-group reproduced in Plate VII*d* from a direct photograph made with the Snow telescope on June 19, 1914, consisted of a larger preceding spot and two smaller spots to the east of it, with various minor companions between them. Plate VII*e*, from a photograph of the spectrum made with the long Nicol and single quarter-wave plate, shows that the two smaller spots were of the same polarity, but opposite to that of the largest spot. Plate VII*f*, taken with the compound quarter-wave plate, not only

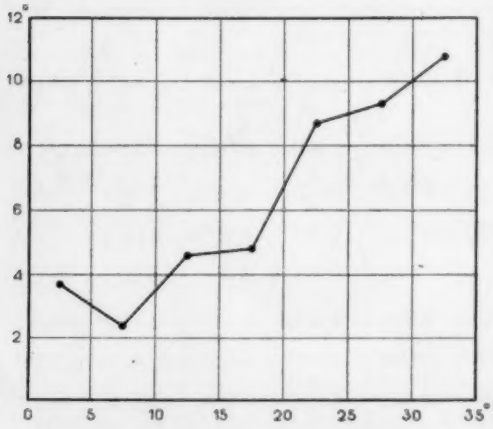


FIG. 5.—Summary of a statistical study of the sun-spot drawings of Carrington and Spörer showing the variation with latitude (abscissae) in the preferential inclination (ordinates) of the axis of bipolar sun-spot groups. In low latitudes the axes are nearly parallel to the sun's equator, but with increasing latitude the mean inclination increases to a maximum of about 11°.

confirms this result, but also serves to better advantage for the study of the weaker fields of the small companion spots lying between the preceding and following members of the group. It will be seen from this figure that magnetic displacements occur at points where no spots are shown, though faint indications of them appear in the original negative.

Analyzing these spectra, we find that there are apparently two "spheres of influence" of opposite polarity which meet near the center of the group. The first of these is dominated by the large preceding spot, while the other comprises the oppositely directed magnetic fields of the two following spots. Minor spots of opposite polarity sometimes occur, as already stated, within these "spheres of influence," but the generality of the bipolar effect is very strikingly shown by an examination of hundreds of spot-groups.

The preceding and following members of bipolar groups may be split into several components, often well separated, and small companion spots, of either polarity, may be present. Furthermore, the strength of the field and the area over which it can be detected may be very different for the preceding and following members of the group. But if magnetic fields of opposite polarity are distinctly shown by the preceding and following members of the pair, the essential characteristics of a bipolar group are present.

The tendency toward bipolar structure is so strongly marked that hardly more than 10 per cent of all spots observed are wholly free from it. In the case of spots which are apparently single, some traces of asymmetry, more or less suggestive of the structure of bipolar groups, can usually be detected. Sometimes such evidence of asymmetry is afforded by faculae following or preceding the spot. More commonly, however, especially in the central part of the sun, it is necessary to have recourse to spectroheliographic plates for the purpose of detecting the asymmetrical structure. In such photographs it is usually found that a single spot, or a group of small spots all having the same magnetic polarity, is near the preceding end of a mass of calcium flocculi elongated in a direction not greatly inclined to the solar equator. Much less frequently the spot occurs near the following end of such a group of flocculi. In

about 10 per cent of all cases hitherto observed here the distribution of the flocculi is fairly symmetrical to the east and west of single spots.

Thus in the magnetic classification of sun-spots it is highly desirable to investigate the magnetic records in the light of information afforded by the distribution of the flocculi. The calcium flocculi serve admirably for the purpose just stated, but in order to study the characteristic vortex structure associated with bipolar spot groups we must have recourse to spectroheliograms of the hydrogen flocculi, taken under high dispersion with the light from the center of the Hα line.

In a later paper the characteristics of these bipolar groups will be discussed more in detail, and a variety of evidence bearing on their nature will be presented. Our immediate purpose is to present a scheme of magnetic classification and to bring out the fact that the recognition of this typical structure, even in the rudimentary form where the second spot is absent[1] and represented only by a train of flocculi, is essential to an intelligent discussion of the distribution of spots of different polarities in the northern and southern hemispheres of the sun.

The methods described above for recording polarities can of course be applied to the more complicated groups as well as to those of the simple bipolar type. A case of unusual complexity is illustrated and described in Plate VIII.

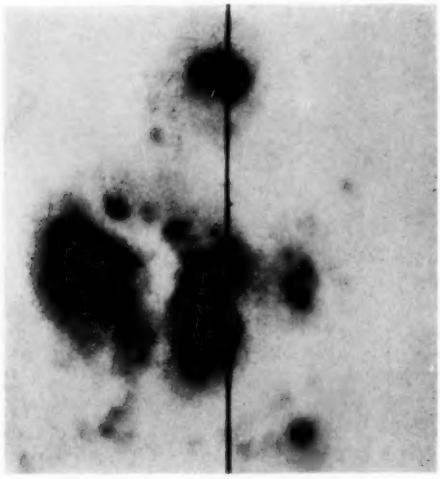
MAGNETIC CLASSIFICATION OF SUN-SPOTS

Our scheme of classifying sun-spots is based primarily upon the determination of their magnetic polarities. Supplementary evidence is frequently needed, however, and this is supplied, as already stated, by calcium and hydrogen spectroheliograms. Three classes of spots are included in the scheme: (α) unipolar, (β) bipolar, and (γ) multipolar. These may be subdivided as indicated below.

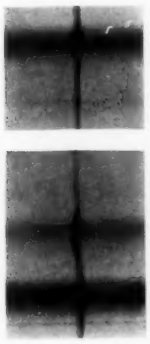
(α) *Unipolar spots.*—Single spots, or groups of small spots, having the same magnetic polarity. It should be noted, however, that

[1] In view of the fact that the general absorption in the spectrum of a spot increases greatly in passing from red to violet, it may perhaps become possible to photograph very faint spots, invisible to the eye, by using ultra-violet light of the shortest possible wave-length.

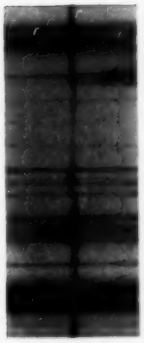
PLATE VIII



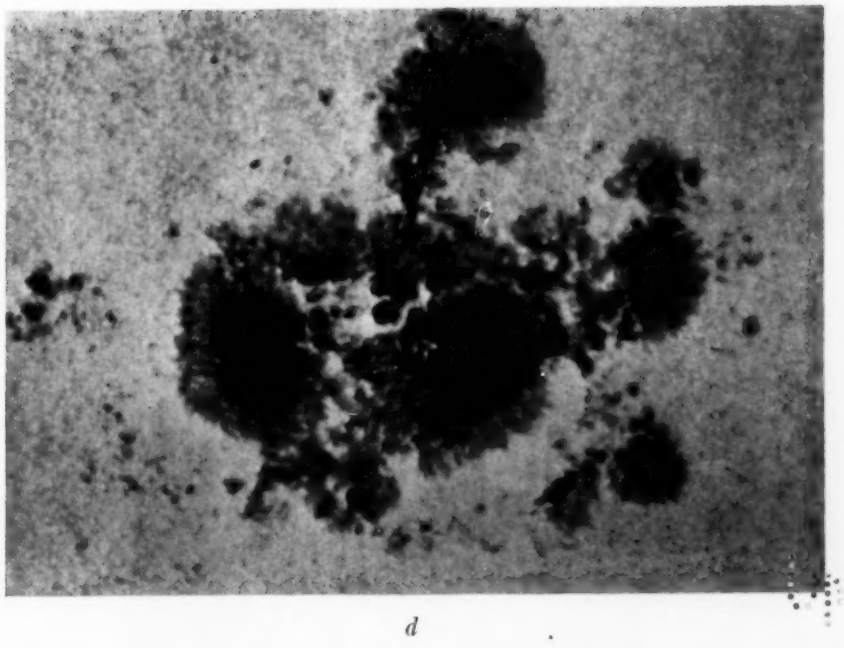
a



b



c

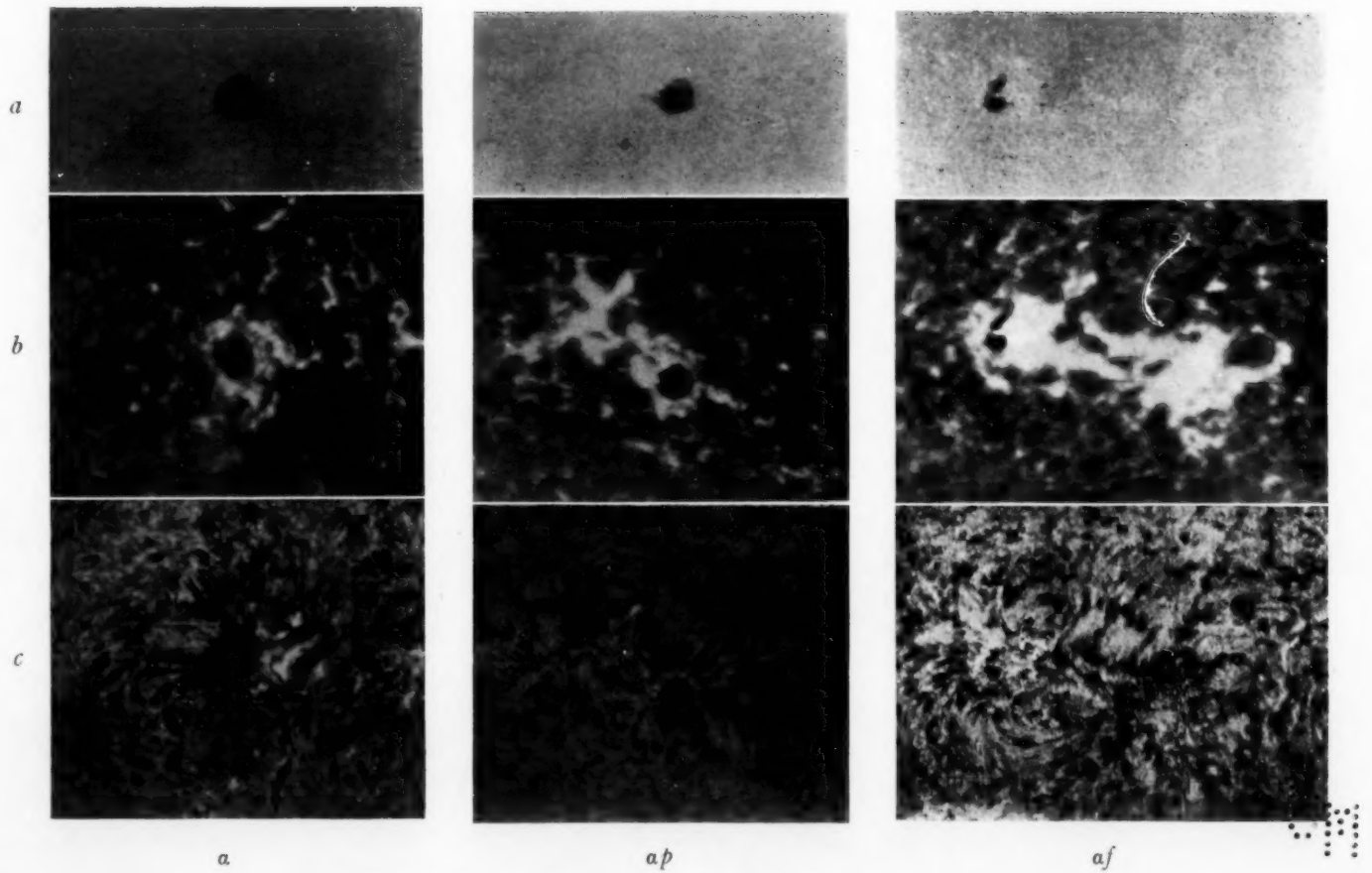


d

a, *b*, *c*, Photographic observations of a multipolar sun-spot group on August 8, 1917, similar to those described in Plate VII*d*, *e*, *f*, the spectral line in this case being the iron triplet λ6173; the lack of definition in *a* is due to poor seeing, together with the fact that it is a photograph of the image of the group formed by the 150-foot telescope, projected on a card mounted above the slit of the spectrograph.

d, An enlarged photoheliogram of the same group made with the 60-foot tower telescope on August 6, 1917, under good atmospheric conditions.

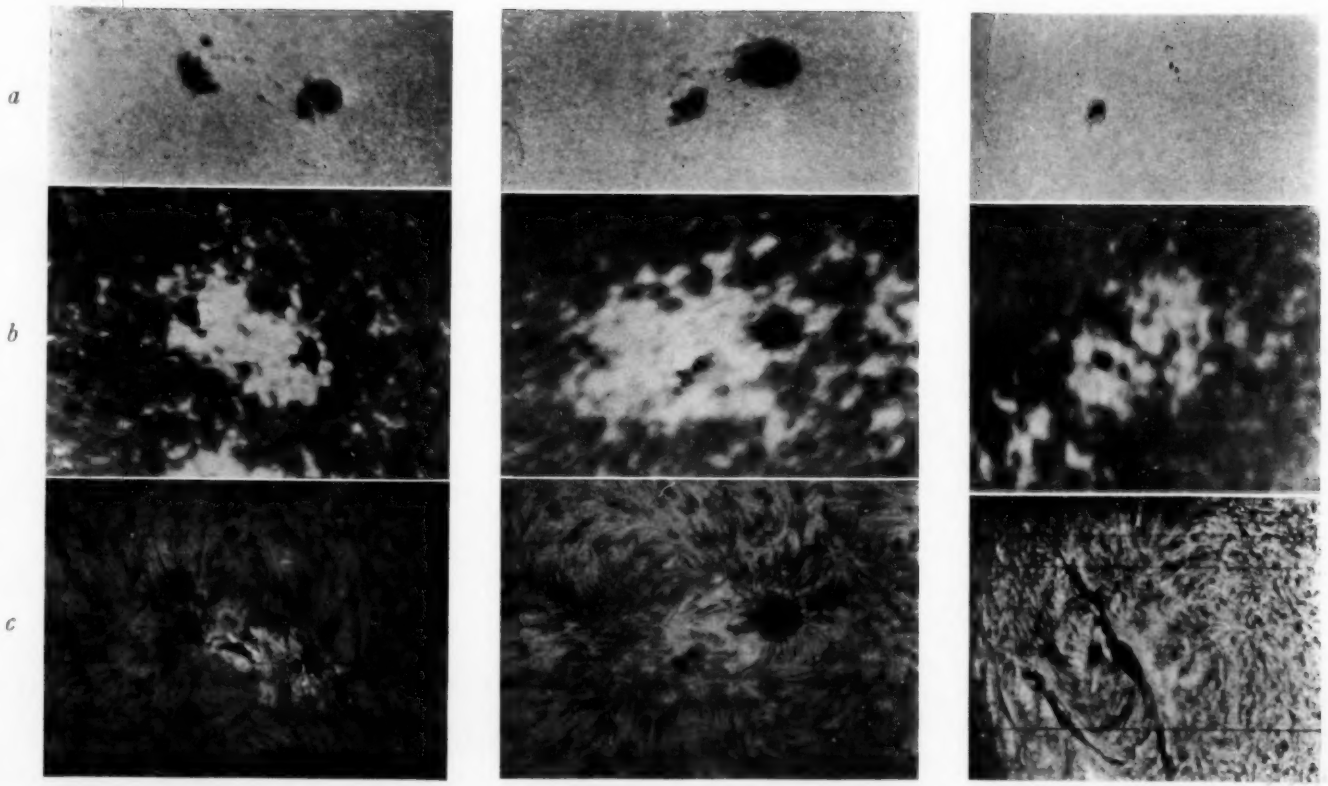
PLATE IX



CLASSIFICATION OF UNIPOLAR SUN-SPOTS

a, Photoheliograms; *b*, K_2 spectroheliograms; *c*, Hα spectroheliograms; **a**, September 3, 1915; **a***p*, September 15, 1914; **a***f*, September 15, 1914.

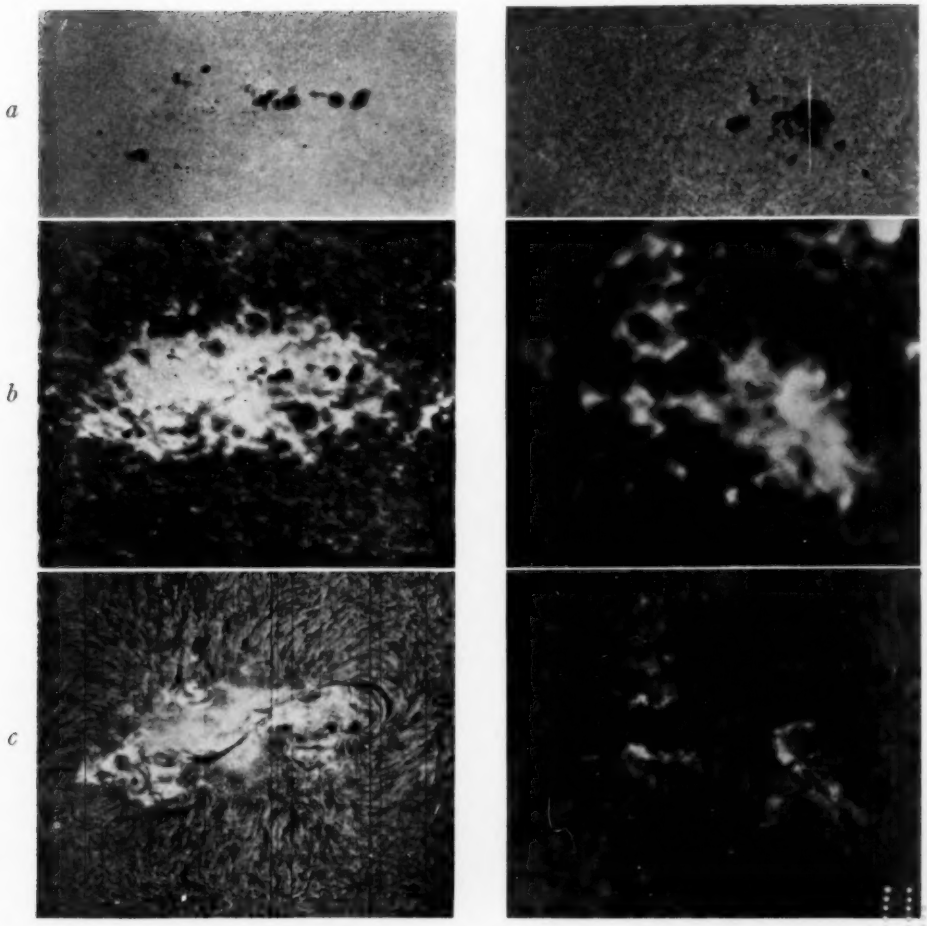
PLATE X



CLASSIFICATION OF BIPOLAR SUN-SPOTS

a, Photoheliograms; *b*, K_2 spectroheliograms; *c*, Hα spectroheliograms; *β*, September 9, 10, 1909; *βp*, July 12, 1914; *βf*, April 22, 1916

PLATE XI



CLASSIFICATION OF MULTIPOLAR SUN-SPOTS

a, Photoheliograms; *b*, K_2 spectroheliograms; *c*, Hα spectroheliograms; $\beta\gamma$, an intermediate type, observed August 5, 1915; γ, July 25, 1917. Plate VIII*d* shows the photoheliogram of a large and unusually complicated γ group.

unipolar spots, and the chief components of bipolar groups, may occasionally have small companions of opposite polarity, which play such a minor and sporadic part in the group that they are disregarded in the classification.

Unipolar spots, whether single or multiple, may be divided into three groups, which are illustrated in Plate IX:

(α) Those in which the distribution of the calcium flocculi is fairly symmetrical preceding and following the center of the group.

(αp) Those in which the center of the spot-group precedes the center of the surrounding calcium flocculi.

(αf) Those in which the center of the spot-group follows the center of the surrounding calcium flocculi.

(β) *Bipolar spots.*—The simplest and most characteristic bipolar spot-group consists of two spots of opposite polarity. The line joining the two spots generally makes only a small angle with the solar equator. Each member of the group may be accompanied or replaced by many small spots, but the great majority of the spots constituting the preceding and following members of the group are of opposite magnetic polarity. One or more companion spots, of polarity opposite to that which characterizes the corresponding region of the group, sometimes occur in association with either the preceding or following member.

Bipolar spots may be divided into four groups, illustrated in Plates X and XI$\beta\gamma$:

(β) Those in which the leading and following members, whether single or multiple, are approximately equal in area.

(βp) Those in which the leading member is the principal member of the group.

(βf) Those in which the following member is the principal member of the group.

($\beta\gamma$) Those in which the preceding or following members are accompanied by minor companions of opposite polarity.

(γ) *Multipolar spots.* Groups of this character, comprising hardly more than 1 per cent of the total number of spots observed, contain spots of both polarities so irregularly distributed as to prevent classification as bipolar groups (see Plates VIII*c* and XIγ).

MAGNETIC CLASSIFICATION OF 970 SUN-SPOTS OBSERVED DURING 1915–1917

While it is obvious that the changes that occur during the life of a spot must preclude a hard-and-fast determination of type, it may be interesting to give the preliminary results of a classification by Nicholson of the spots observed since our present method of recording was put into effect in 1915. In presenting the following figures it should be stated that they are provisional, and therefore subject to revision in the light of further study. Table III is self-explanatory, giving the number of spots observed in both hemispheres during 1915, 1916, and 1917, classified according to the system already explained.

Several interesting facts are brought out by this table. Most notable of these is the strong tendency toward the bipolar type, indicated not only by the large percentage of bipolar groups, but also by the small proportion of symmetrical unipolar spots. Another striking fact is the dominance of preceding spots, shown by the high percentage of βp spots as contrasted with βf spots, and also indicated by a similar preponderance of αp over αf spots. The constancy of the percentages for the successive years, and the very small number of multipolar (γ) spots, should also be noted.

The results of magnetic observation, revealing the great preponderance of bipolar groups, are closely in harmony with the conclusion reached by Father Cortie in his valuable paper "On the Types of Sun-Spot Disturbances."[1] After describing the various types, he remarks:

> The chief type, however, of which the above mentioned are in most, possibly in all, cases but phases, is the double-spot formation, with a train of smaller spots between the two principal spots of the group, the whole group generally drifting into more or less parallelism with the solar equator. In this form the principal spot, which eventually becomes a normal spot of regular outline, is generally the leading spot, but in many cases it is the following spot, while sometimes the preponderance in area alternates between the two, as the group traverses the disk. In yet rarer instances both the chief spots develop as regular spots.

A discussion of the details of sun-spot formation and dissolution, and of the relationship between spot polarities and the structure

[1] *Astrophysical Journal*, 13, 260, 1901.

of the accompanying hydrogen flocculi, must be reserved for another paper. Here it is our purpose to consider only such phases of these and other questions as bear directly upon the derivation of a law of sun-spot polarities.

TABLE III

MAGNETIC CLASSIFICATION OF 970 SPOTS

		a	ap	af	β	βp	βf	$\beta\gamma$	γ	Unclassified	Total
1915	N	10	17	5	17	29	3	4	3	11	99
	S	7	16	4	21	22	6	4	0	3	83
	Total	17	33	9	38	51	9	8	3	14	182
	Percentages	9	18	5	21	28	5	4	2	8	
Total percentages			32			58					
1916	N	22	26	4	49	63	12	7	0	8	191
	S	31	28	8	17	37	13	6	0	7	147
	Total	53	54	12	66	100	25	13	0	15	338
	Percentages	16	16	4	20	30	7	4	0	4	
Total percentages			35			61					
1917	N	25	54	2	66	62	17	9	3	3	241
	S	16	41	7	53	69	11	7	0	5	209
	Total	41	95	9	119	131	28	16	3	8	450
	Percentages	9	21	2	26	29	6	4	1	2	
Total percentages			32			65					

SUMMARY (PERCENTAGES)

	a	ap	af	β	βp	βf	$\beta\gamma$	γ	Unclassified
1915	9	18	5	21	28	5	4	2	8
1916	16	16	4	20	30	7	4	0	4
1917	9	21	2	26	29	6	4	1	2
Mean	11	18	4	22	29	6	4	1	5
Total number of spots	111	182	30	223	282	62	37	6	37

POLARITIES OF SPOTS IN THE NORTHERN AND SOUTHERN HEMISPHERES

For the purpose of deriving a law of sun-spot polarities we may regard unipolar spots (ap) followed by a train of flocculi as preceding spots of incomplete bipolar groups, and those (af) which are

preceded by a train of flocculi as following spots of such groups. During the last sun-spot cycle (observations from June 1908 to December 1912) it was found in the great majority of spots observed that the "marked strip" of the compound quarter-wave plate transmitted the violet component of preceding spots in the Northern Hemisphere and of following spots in the Southern Hemisphere.[1] It naturally follows, from the characteristics of bipolar groups, that during the same period the marked strip transmitted the red component of following spots in the Northern Hemisphere and of preceding spots in the Southern Hemisphere. The numbers of spots observed are given in Table IV.

TABLE IV

	Regular			Irregular			Range in Latitude	Average Latitude
	V_p^N–R_f	R_p^S–V_f	Total	N	S	Total		
Last cycle..... (June 1908 to December 1912)	7	17	24	0	2	2	18° to 3°	9°

Thus while the bipolar characteristic of sun-spots introduces an element not encountered in the case of terrestrial storms, the opposition in polarity north and south of the solar equator is analogous to the opposite direction of whirl, invariably observed in the case of northern and southern cyclones and tornadoes.

After the sun-spot minimum, which occurred in December 1912, we found, to our surprise, that the polarity of the members of bipolar groups was opposite to that observed before the minimum. That is to say, the marked strip of the compound quarter-wave plate now transmits the red component of the preceding spots of bipolar groups in the Northern Hemisphere and the violet component of the preceding spots of bipolar groups in the Southern Hemisphere.

This sudden change was so remarkable that it was feared some observational error had been made. The results have been checked

[1] Few spots were observed during this cycle, because attention was then concentrated upon a small number of very large spots.

repeatedly by different observers, however, and in all cases the conclusion has been the same. The first observations of the former cycle were made with the 60-foot tower telescope and 30-foot spectrograph, but before the end of the cycle the 150-foot tower telescope and 75-foot spectrograph were put into commission, and this work was transferred from the old to the new tower. Thus the danger of any confusion due to the change of spectrographs and polarizing apparatus was eliminated, as the results obtained with the 150-foot tower telescope during the former cycle were in harmony with those secured with the 60-foot tower telescope during the same period. During the former cycle the observations were both visual and photographic, but since the beginning of the present cycle most of the polarities have been determined visually, though the results have frequently been checked photographically.

TABLE V

Present Cycle	Regular			Irregular			Range in Latitude	Average Latitude
	N R_p–V_f	S V_p–R_f	Total	N	S	Total		
1913, 1914.....	18	14	32	1	1	2	34° to 13°	22°
1915.....	73	68	141	2	0	2	29 " 2	19
1916.....	166	120	286	7	7	14	37 " 4	17
1917.....	221	193	414	8	6	14	30 " 1	14

The observations of the present cycle are given in Table V, which corresponds with Table IV except for the fact that in Table V the polarities are classed as "regular" when the marked strip transmits the red component in preceding spots of the Northern Hemisphere, whereas during the former cycle it transmitted the violet component in such spots.

In a preliminary paper describing the observed change of polarity at the last sun-spot minimum,[1] it was suggested that the explanation might be connected with the difference in latitude of the spots of the old and new cycles. The mean latitude of the spots observed during the old cycle was 9°, while that of the spots

[1] Hale, *Mount Wilson Communication*, No. 10; *Proceedings National Academy of Sciences*, 1, 385, 1915.

observed up to that date during the new cycle was 23°. It therefore seemed possible that there might be two zones on the sun, of low and high latitude, in which the polarities of spots were of opposite sign.

This view of the case, however, has not been borne out by time, as the results given in Table V indicate. The percentage of irregular spots has not increased materially during the present cycle, although their mean latitude has decreased from 22° in 1913–1914 to 14° in 1917. The maximum of solar activity has also definitely passed, so that it can hardly be supposed that any reversal of polarity will be observed before the close of the cycle, unless it should be found to lag considerably behind the maximum.

DISCUSSION OF RESULTS

The present investigation should ultimately lead to the formulation of a definite law of sun-spot polarities, from which the polarities of normal spots of any type can be predicted for either hemisphere and for any epoch in the sun-spot cycle. We already know that the preceding and following spots of binary groups, with few exceptions, are of opposite polarity, and that the corresponding spots of such groups in the Northern and Southern hemispheres are also opposite in sign. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle (see Fig. 6, in which these results are expressed graphically). It is evident, however, that the formulation of a law of polarities cannot be undertaken until after the close of the present cycle, when it will be learned whether a reversal of sign is actually characteristic of the sun-spot minimum.

After an empirical law of spot polarities has been formulated, the problem of its interpretation will remain. The possibility of expressing such a law in the same terms that apply in the case of terrestrial storms depends upon the possession of data still beyond our reach. Thus the view that sun-spots are vortices depends upon the assumption that the magnetic field must be caused by electrically charged particles whirling in a vortex. Supposing that the existence of a true hydrodynamical vortex and the direction of the

whirl within it can be determined by observations of the Evershed effect, or in some other way, the sign of the dominant charge will follow at once from our knowledge of the magnetic polarity of the spot in question. Or, if the sign of the charge can be independently found, the direction of the whirl will follow.

In Hale's first paper on the Zeeman effect in sun-spots, the sign of the dominant charge was found to be negative by proceeding on the assumption that the direction of whirl in the spot vortex coincides with that in the hydrogen vortex above it. A long series of observations of the hydrogen flocculi has since shown that this assumption is probably unwarranted. A good majority of the hydrogen whirls associated with preceding spots are right-handed in the Southern Hemisphere and left-handed in the Northern Hemisphere, as in the case of terrestrial storms, but there are many exceptions to this rule. Moreover, the hydrogen whirls showed no reversal of direction at the sun-spot minimum, and during the present cycle we have found cases in which either right-handed or left-handed hydrogen whirls are associated with spots of a given polarity. The whole subject is so complex that it will be advantageous to postpone further discussion until the great mass of observational material at our disposal can be more exhaustively studied.

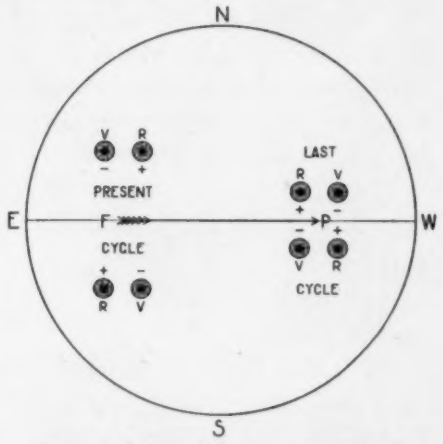


FIG. 6.—Diagram summarizing the results of polarity observations of sun-spots during the present and last cycles. The arrow indicates the direction of the sun's rotation; the letters *R* and *V*, the components of a normal triplet transmitted by the "marked strip" of the compound quarter-wave plate; and the algebraic signs, the distribution of the polarities between the preceding and following members of a bipolar group. Unipolar spots are normally of the same polarity as the preceding members of bipolar groups in the same hemisphere.

SUMMARY

1. The magnetic polarity of a sun-spot can be determined by observations, made with Nicol and quarter-wave plate, of the relative intensities of the *n*-components of a Zeeman triplet in its spectrum.

2. Such determinations of polarity can be made at almost any position on the sun's disk, but certain precautions must be taken to avoid error in the case of spots near the limb.

3. The inclination of the lines of force in sun-spots can be measured with considerable precision.

4. About 60 per cent of all sun-spots are binary groups, the single or multiple members of which are of opposite magnetic polarity.

5. Unipolar spots usually exhibit some of the characteristics of bipolar groups.

6. Before the last sun-spot minimum, the magnetic polarity of unipolar spots and of the preceding members of bipolar spots was positive in the southern and negative in the northern hemispheres of the sun.

7. Since the minimum these signs have been reversed.

8. The paper describes a scheme of classifying sun-spots on the basis of their magnetic properties.

9. The results of a magnetic classification of 970 spots observed during the years 1915–1917 are briefly summarized.

MOUNT WILSON SOLAR OBSERVATORY
November 11, 1918

THE MOTIONS IN SPACE OF SOME STARS OF HIGH RADIAL VELOCITY[1]

By WALTER S. ADAMS and ALFRED H. JOY

The determinations of radial velocity made at the Lick and Mount Wilson observatories during the past few years have added greatly to the number of stars known to have large velocities in the line of sight. Most of these stars have well-determined proper motions and for many of them parallaxes have been measured by numerous observers. The motions in space of these stars are of interest because of the velocities with which they move and the wide range in spectral type and absolute magnitude which is found among them.

A list of all stars with radial velocities exceeding 80 km for which proper motions and parallaxes (derived either by the trigonometric or the spectroscopic method) are known is given in Table I. The stars are numbered consecutively, and the successive columns give the positions for 1900, their apparent visual magnitudes, spectral types, proper motions and direction of proper motion, radial velocities and radial velocities corrected for the solar motion. The latter are derived from the apex determined by Strömberg,[2] $A_0 = 270°.9$, $D_0 = +29°.2$, $V_0 = 21.5$ km. The apparent magnitudes are from Harvard determinations, the spectral types from Mount Wilson observations, and the proper motions have in most cases been taken from the catalogues of Boss and Porter.[3] The radial velocities are from the Lick and Mount Wilson determinations, the values being combined when the same star has been investigated at both observatories.

The parallaxes of all of the stars in the list with the exception of five have been derived from the absolute magnitudes determined spectroscopically at Mount Wilson. Small systematic corrections

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 163

[2] *Mt. Wilson Contr.*, No. 144; *Astrophysical Journal*, 47, 7, 1918.

[3] *Publications of the Cincinnati Observatory*, No. 18, Parts 1–4, 1915–1918.

TABLE I

No.	Name	α (1900)	δ (1900)	m	Spec.	μ	ψ	V	V
								km	km
1	ε Andromedae	0^h33^m3	+28°46′	4.5	G5	0″.336	222°	− 84	− 81
2	μ Cassiopeiae	1 1.6	+54 26	5.3	G5	3.760	114.5	−. 97	− 91
3	Lalande 1966	1 3.3	+61 1	7.9	F5	0.638	86	−325	−318
4	Lalande 4855	2 32.6	+30 24	7.2	F8	0.625	231	− 99	−103
5	Lalande 5761	3 2.5	+25 58	8.0	A3p	0.861	194	−144	−151
6	W.B. 3^h617	3 35.3	− 3 32	7.2	F6	0.745	107	+114	+ 99
7	A.G.Berl. 1366	4 8.6	+22 6	8.9	Fo	0.54	125	+330	+328
8	Groom. 864	4 34.5	+41 56	7.3	G2	0.690	127	+105	+ 99
9	Cordoba 5^h243	5 7.7	−44 59	9.2	G-K	8.75	131	+242	+222
10	Lalande 9960	5 14.1	− 3 11	8.5	K5	0.721	78	+ 86	+ 68
11	φ Orionis	5 31.4	+ 9 14	4.4	G7	0.321	163	+ 99	+ 82
12	δ Leporis	5 47.0	−20 53	3.9	G7	0.696	160	+ 99	+ 78
13	A.G.Berl. 1866	5 57.3	+19 23	9.0	F9	0.76	129	−190	−204
14	Boss 1511	5 59.2	−26 17	5.2	K3p	0.104	24	+183	+162
15	θ Can. Maj.	6 49.5	−11 55	4.2	K4	0.137	264	+ 97	+ 77
16	Groom. 1281	7 8.4	+47 25	5.6	Go	0.184	168	+ 88	+ 83
17	Lalande 15290	7 47.2	+30 55	8.2	F7	1.962	158	−242	−251
18	Lalande 19821	10 6.3	+24 15	8.5	G2	0.414	279	+ 81	+ 77
19	Lalande 21185	10 57.9	+36 38	7.6	Ma	4.779	187	− 87	− 85
20	Groom. 1830	11 47.2	+38 26	6.5	G8	7.047	145	− 97	− 92
21	Lalande 23995	12 47.9	−17 57	8.2	F3	0.877	159	+144	+144
22	Lalande 27274	14 54.2	−21 36	8.3	F4	0.785	229	+160	+168
23	A. Oe. 14318, A. Oe. 14320	15 4.7	−15 59	9.6	Ko G8	3.682	196	+300	+310
24	Lalande 28607	15 37.7	−10 36	7.3	A2p	1.178	256	−170	−157
25	A.G.Leid. 5734	16 11.4	+32 24	(8.3)	K4	0.035	145	−164	−144
26	Boss 4188	16 22.3	− 7 22	5.4	Mb	0.176	168	+ 97	+112
27	Σ 2173	17 25.2	− 0 59	5.9	G6	0.214	215	− 81	− 63
28	W.B. 17^h514	17 29.9	+ 6 4	8.6	F5	0.623	311	−148	−129
29	Barnard's Star	17 53.0	+ 4 28	9.7	Mb	10.27	356	−106	− 87
30	31 b Aquilae	19 20.2	+11 44	5.2	G7	0.961	49	− 98	− 78
31	α Vulpeculae	19 24.5	+24 28	4.6	Ma	0.170	227	− 86	− 66
32	Lalande 37120	19 29.7	+32 59	6.6	Fo	0.517	294	−162	−142
33	A. Oe. 20452	20 17.7	−21 40	8.1	F5	1.182	154	−179	−168
34	η Cephei	20 43.3	+61 27	3.6	G8	0.826	7	− 87	− 71
35	Boss 5482	21 16.6	+23 26	5.8	Go	0.252	123	− 88	− 73
36	W.B. 21^h502	21 24.5	−12 56	9.1	K5	1.052	105	− 90	− 81
37	W.B. 21^h594	21 26.0	+45 27	7.5	G8	0.56	50	− 83	− 67

have been applied to these values in accordance with an unpublished investigation by Strömberg. These corrections are as yet provisional and in nearly all cases their influence is slight. The directly measured parallaxes have been used in the case of stars numbered 5, 9, 23, 24, and 29. For star No. 27, which is a close visual binary, the apparent magnitude of the brighter component has been employed. The derivation of the parallaxes is from the formula $\log \pi = 0.2(M-m)-1$, and the values of the absolute magnitude and parallax are given in the second and third columns of Table II.

TABLE II

No.	M	π	A	D	x	y	z	v	L	B
					km	km	km	km		
1	+ 0.9	+0.019	211°	−29°	+ 26	− 70	+ 44	87	290°	+30°
2	+ 5.7	0.120	112	−42	−115	−103	− 28	156	222	−10
3	+ 3.9	0.016	152	−47	−155	−326	+ 49	364	245	+ 8
4	+ 4.4	0.028	275	−40	+117	− 92	− 35	153	322	−13
5	+ 6.0	0.039	247	−54	+ 89	−155	− 13	179	300	− 4
6	+ 4.4	0.028	103	−13	−148	− 34	− 11	152	193	− 4
7	+ 3.0	0.007	101	− 8	−489	− 63	− 28	494	187	− 3
8	+ 6.0	0.055	94	+29	− 93	+ 52	+ 14	108	151	+ 7
9	+11.7	0.319	123	−59	−121	−219	− 57	257	241	−13
10	+ 7.0	0.050	121	+12	− 87	+ 3	+ 38	95	178	+24
11	+ 1.0	0.021	94	−26	− 92	− 35	− 29	102	200	−16
12	+ 1.4	0.032	126	−66	− 45	−116	− 31	128	249	−14
13	+ 5.6	0.021	230	−36	+134	−212	+ 74	262	302	+16
14	+ 0.6	0.012	95	−13	−163	− 26	− 30	168	189	−10
15	− 0.4	0.012	69	−10	− 77	+ 7	− 49	91	175	−33
16	+ 5.5	0.095	116	+54	− 47	+ 54	+ 43	84	131	+31
17	+ 5.0	0.023	217	−70	+ 73	−457	− 70	467	279	− 9
18	+ 6.0	0.032	115	+35	− 73	+ 38	+ 41	91	153	+27
19	+10.8	0.437	328	−61	+ 31	− 58	− 68	95	298	−46
20	+ 6.5	0.100	243	−50	+180	−301	+ 2	351	301	0
21	+ 3.6	0.012	266	−66	+143	−321	−122	372	294	−19
22	+ 3.8	0.013	156	−45	−128	−289	+ 62	322	246	+11
23	+ 7.8 7.4	0.044	200	−64	+ 38	−489	− 10	491	274	− 1
24	+ 4.9	0.033	98	0	−221	+ 4	− 8	221	179	− 2
25	+ 0.1	0.002	33	−51	− 40	− 71	−144	166	241	−60
26	− 0.6	0.006	266	−51	+101	−128	− 35	167	308	−12
27	+ 5.1	0.069	86	− 1	− 61	+ 6	− 14	63	174	−13
28	+ 4.4	0.014	130	+31	−182	+ 68	+148	245	159	+37
29	+13.4	0.540	92	+45	− 92	+ 89	+ 30	132	136	+13
30	+ 5.4	0.110	94	+11	− 86	+ 20	− 2	89	167	− 1
31	+ 0.4	0.014	158	−42	− 36	− 78	+ 23	89	245	+15
32	+ 5.1	0.050	134	−24	−116	− 89	+ 40	152	217	+15
33	+ 4.0	0.015	96	−36	−314	−194	−130	391	212	−19
34	+ 3.0	0.076	136	−29	− 60	− 56	+ 19	84	223	+13
35	0.0	0.007	63	−39	−107	− 60	−123	174	209	−45
36	+ 8.7	0.083	112	+ 9	− 88	+ 5	+ 23	91	177	+15
37	+ 5.9	0.048	120	−17	− 73	− 33	+ 12	81	204	+ 9

The computation of the equatorial velocity-components referred to the sun, ξ, η, and ζ, has been made from the formulae

$$\xi = V \cos \alpha \cos \delta - \frac{k}{\pi}(\mu_1 \sin \alpha + \mu_2 \cos \alpha \sin \delta)$$

$$\eta = V \sin \alpha \cos \delta + \frac{k}{\pi}(\mu_1 \cos \alpha - \mu_2 \sin \alpha \sin \delta)$$

$$\zeta = V \sin \delta + \frac{k}{\pi}\mu_2 \cos \delta$$

In these expressions V is the radial velocity, $k = 4.737$ and $\mu_1 = \mu_\alpha \cos \delta$, $\mu_2 = \mu_\delta$ where μ_α and μ_δ are the components of the

proper motion. To reduce these values to the usually adopted centroid of the stars by eliminating the solar motion, we put:

$$\xi_0 = V_0 \cos A_0 \cos D_0$$
$$\eta_0 = V_0 \sin A_0 \cos D_0$$
$$\zeta_0 = V_0 \sin D_0$$

in which V_0 is the solar motion, and A_0 and D_0 the right ascension and declination of its apex. We then have for the equatorial components of the star's space-velocity,

$$\xi_1 = \xi + \xi_0 = v \cos A \cos D$$
$$\eta_1 = \eta + \eta_0 = v \sin A \cos D$$
$$\zeta_1 = \zeta + \zeta_0 = v \sin D$$

From these equations we calculate not only ξ_1, η_1, and ζ_1, but also v, A, and D, the space-velocity of the star and the co-ordinates of its apex. Using the values already referred to we have

$$\xi_0 = 0, \qquad \eta_0 = -19, \qquad \zeta_0 = +10$$

The components of velocity with reference to the galactic system are found from the equations

$$x = v \cos L \cos B = +0.1846\ \xi_1 - 0.9828\ \eta_1$$
$$y = v \sin L \cos B = +0.4494\ \xi_1 + 0.0844\ \eta_1 + 0.8893\ \zeta_1$$
$$z = v \sin B \qquad = -0.8740\ \xi_1 - 0.1642\ \eta_1 + 0.4573\ \zeta_1$$
$$v^2 = x^2 + y^2 + z^2.$$

The numerical coefficients result from the assumed values $\alpha = 190°.6$, $\delta = +27°.2$ for the pole of the galaxy.

The results of the computations are given in Table II. A and D are the right ascensions and declinations of the apices, x, y, and z the components of velocity referred to the galaxy, v is the total velocity, and L and B the galactic co-ordinates of the apices. The values are shown graphically in Fig. 1, the plane used being that of the galaxy. The apices are shown in projection, and the vectors drawn from the origin represent the direction and amount of motion in this plane.

Some of the conclusions to be drawn from these results may be summarized as follows:

1. The components of velocity normal to the plane of the galaxy are much smaller than those in the plane. Thus we find from Table II the average values:

$$x = 115 \text{ km}, \qquad y = 119 \text{ km}, \qquad z = 46 \text{ km}.$$

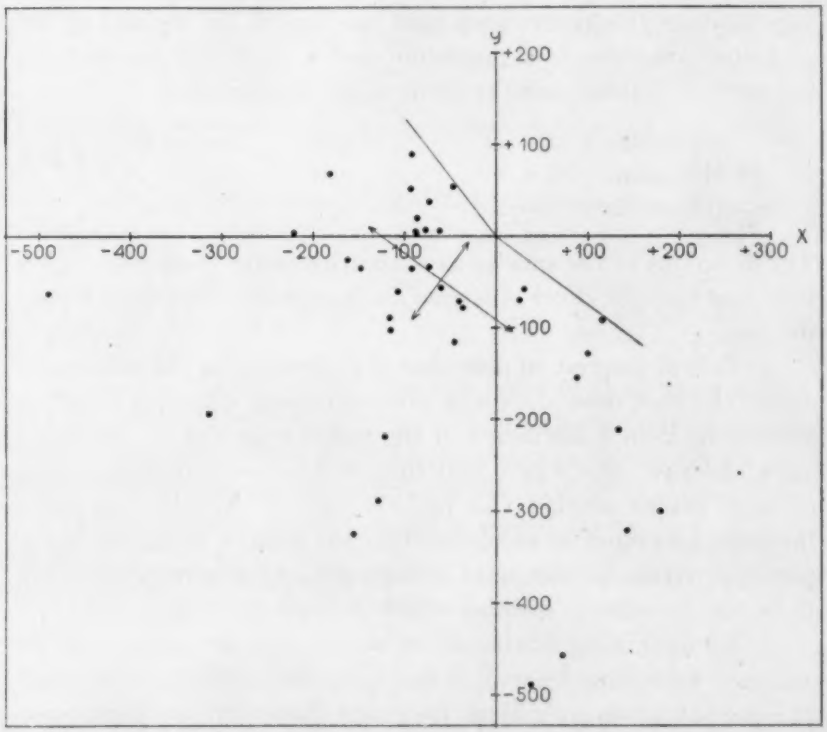


FIG. 1.—Projection on galactic plane of apices of motion of thirty-seven stars of high radial velocity. The vectors drawn from the origin represent the projected velocities in km per sec. The axes of the ellipse of intersection of the velocity-ellipsoid with the galactic plane are indicated by the two arrow-headed lines.

The same result follows from a consideration of the latitudes B of the apices. The latitudes of only six of the thirty-seven stars exceed 30°.

2. Nearly an entire hemisphere is devoid of apices, the galactic longitudes all lying between 131° and 322°.

3. The velocity of the centroid of these stars is remarkably high. Thus omitting those with total velocities greater than 300 km we find from the remaining twenty-nine stars:

$$\bar{x} = -59.5 \text{ km} \qquad \bar{y} = -44.5 \text{ km} \qquad \bar{z} = -4.4 \text{ km}$$
$$v = 74.4 \text{ km} \qquad L = 217^\circ \qquad B = -3^\circ$$

4. If we project the velocities of these twenty-nine stars upon axes through this center such that the sum of the squares of the projected velocities is a maximum and a minimum we find the following directions[1] and the mean square dispersion σ:

Maximum:	$L = 141^\circ$	$B = +9^\circ$	$\sigma = 100.6$ km
Minimum:	$L = 61^\circ$	$B = -49^\circ$	$\sigma = 46.1$ km
Intermediate:	$L = 43^\circ$	$B = +39^\circ$	$\sigma = 61.4$ km

The directions of the smaller axes are necessarily uncertain. Thus it is clear that the effect of stream motion among these stars is very marked.

5. It is of interest to note that the direction of the major axis as derived from these stars is in close agreement with that found by Strömberg from a discussion of the radial velocities of 260 dwarf stars ($L = 148^\circ$, $B = +14^\circ$), and that of Raymond[2] from 559 stars of large proper motion ($L = 146^\circ$, $B = +8^\circ$). All three of these investigations agree in indicating that the galactic longitude of the principal vertex for the stars of high velocity is considerably less than that for stars in general, which is about 170°.

6. An interesting feature of the results, but one which must be accepted with some reserve, is the apparent tendency of the stars to move along a line of galactic longitude about 260°, the assumption being made of a motion of the centroid of $\bar{x} = -100$ km, $\bar{y} = -20$ km. This direction coincides nearly with that of the greatest star-density as determined by Charlier, Walkey, Nort, and Plummer.

7. Reference may perhaps also be made to the tendency shown by the stars of the very highest velocity (over 300 km) to move along a line parallel to that of the major axis, referring the motion

[1] The intersection of this velocity-ellipsoid with the galactic plane is indicated in Fig. 1 by straight lines which show the axes of the ellipse of intersection.

[2] *Astronomical Journal*, 30, 191, 1917.

to their common center. Thus all of the stars omitted from the previous discussion show a very fair degree of alignment with the direction of the principal axis as given in Fig. 1.

8. A marked difference is seen in the average galactic latitudes of the apices of the stars of high and low luminosity, the latter lying more nearly in the plane of the galaxy. Thus if we select the stars of absolute magnitude brighter and fainter than 3.0 we find:

	Average M	Average B
9 stars	+0.4	26°
28 stars	5.9	14°

The galactic latitudes of the apices of only four of the fainter stars exceed 26°.

9. A similar result is found for the average velocities of the stars of high and low luminosity, the latter stars moving more rapidly.

	Average M	Average v
9 stars	+0.4	130 km
28 stars	5.9	216 km

10. An examination of the spectral types of these stars shows that an extraordinarily large proportion, twenty-six out of thirty-seven, are of types F and G. The stars of type F have by far the largest average space motion, nearly double that of the stars of type G. The comparison, which is of little weight for types A, K and M, gives:

No. of Stars	Type	Average v	Average V'
		km	km
2	Ap	200	115
11	F	307	187
15	G	156	104
5	K	122	106
4	M	121	88

Among the stars of type F it is of interest to note that those of earlier spectrum show the largest velocities. Thus the six stars with spectra between Fo and F5 inclusive have space motions of 364, 494, 372, 322, 245, and 391 km, an average value of 365 km. The average value of V′ for these stars is 209 km.

MOUNT WILSON SOLAR OBSERVATORY
January 1919

THE ORBITS OF THREE SPECTROSCOPIC BINARIES[1]

By WALTER S. ADAMS and ALFRED H. JOY

THE ORBIT OF BOSS 593

The two stars Boss 592 and 593 ($\alpha = 2^h\ 31^m.2$; $\delta = +24°\ 13'$; 1900) form the well-known double star 30 Arietis, or Σ 5, with a distance of 38″ and a common proper motion of 0″.146 annually. The visual magnitudes of the stars are 7.4 and 6.6 respectively, and the spectral types are very similar, being F5 and F4 according to our most recent determinations. The brighter star of the pair,

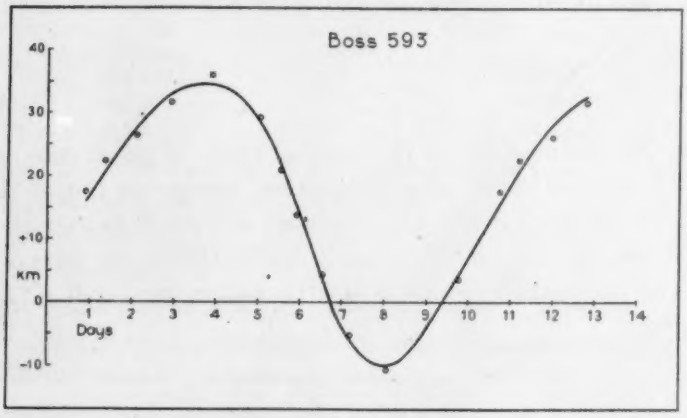


FIG. 1

Boss 593, was found in 1916 to be a spectroscopic binary, and the number of spectrograms is now sufficient to make a determination of its orbit readily possible.

All of the spectrograms were secured with the Cassegrain spectrograph and the 60-inch reflector, a dispersion of one prism and a camera of 18 in. (45.7 cm) focal length being used throughout the observations. The spectrum is not of the best quality for measurement, and the lines are broad and somewhat hazy. For

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 164.

this reason, and because of the low dispersion employed, the computation of the orbit has been based upon normal positions, the radial velocities for spectrograms taken at nearly the same phase being combined to give mean values.

Since the observations extend over an interval of three years, it has been possible to determine the period with considerable accuracy. This is found to be closely 9.851 days. With the aid of this period the phases have been determined and the radial velocities combined into the normal values given in Table I. The epoch selected is December 20.0, 1917, Julian day 2421583.0 G.M.T.

TABLE I

No.	No. of Plates	Phase	V	O−C$_1$	O−C$_2$	O−C$_3$
		Days	km	km	km	km
1.....	2	0.910	+36.2	+1.1	+2.1	+1.5
2.....	2	2.008	+29.4	+0.8	+1.0	+0.9
3.....	2	2.531	+21.0	−0.4	−0.9	−0.8
4.....	3	2.931	+14.2	−0.4	−1.1	−0.9
5.....	4	3.551	+ 4.3	+0.6	+0.3	+0.5
6.....	4	4.188	− 5.3	0.0	+0.2	+0.5
7.....	1	5.081	−10.5	−0.5	−1.1	−0.4
8.....	2	6.778	+ 3.8	−1.2	−1.3	−0.9
9.....	2	7.759	+17.6	+1.0	+1.6	+1.5
10.....	1	8.207	+22.3	+1.3	+1.7	+1.3
11.....	2	8.976	+26.0	−1.2	−1.2	−1.8
12.....	2	9.784	+31.5	−0.8	−0.7	−1.4

The method of calculation adopted is that involving the use of a Fourier's series, the details of which are given by Plummer,[1] Russell,[2] and others. The mean radial velocities and phases of Table I were plotted, and a smooth curve was drawn through the corresponding points. From this curve were read off the radial velocities $V_0, V_1 \ldots V_{11}$ for each twelfth part of the period. The following equation was then assumed:

$$V = b_0 + b_1 \cos \tau + b_2 \cos 2\tau + a_1 \sin \tau + a_2 \sin 2\tau.$$

The value of τ being 30°, the computation of the coefficients is made readily from the relationships

$$b_0 = \tfrac{1}{12}\sum_{0}^{11} V_n; \quad b_1 = \tfrac{1}{6}\sum_{0}^{11} V_n \cos n.30°; \quad b_2 = \tfrac{1}{6}\sum_{0}^{11} V_n \cos n.60°; \text{ etc.}$$

[1] *Astrophysical Journal*, **28**, 212, 1908. [2] *Ibid.*, **15**, 252, 1902.

The resulting value for the series is:

$$V=+14.42+21.31\cos\tau-3.08\cos 2\tau+4.96\sin\tau+15.1\sin 2\tau.$$

The normal values of the radial velocities are well represented by this expression, as the residuals given in Table I under $O-C_1$ show.

Approximate values of the elements may be derived from the coefficients of this series by means of the relationships given by Plummer. Neglecting the second and higher powers of the eccentricity we find:

$$\gamma=+14.4 \text{ km}$$
$$K=21.9 \text{ km}$$
$$\omega=127^\circ.6$$
$$e=0.157$$
$$T=\text{J.D. } 2421586.86$$
$$P \text{ (assumed)}=9.851 \text{ days}$$
$$a\sin i=2{,}925{,}000 \text{ km}$$
$$\frac{m_1^3\sin^3 i}{(m+m_1)^2}=0.010\ \odot$$

The values of the radial velocity calculated from these elements show the differences from the observed values given in Table I under $O-C_2$.

Although this representation is satisfactory in view of the degree of accuracy obtained in the measurements of the radial velocity, it seemed desirable to carry out a least-squares solution for the purpose of obtaining the probable errors of the various elements. In this solution the period P was assumed to be constant, and corrections were determined for γ_0, ω, e, K, and T. The final values of the resulting elements are as follows:

$$\gamma=+14.42\pm0.71 \text{ km}$$
$$K=22.48\pm0.47 \text{ km}$$
$$\omega=129^\circ.6\pm7^\circ.3$$
$$e=0.1455\pm0.0185$$
$$T=\text{J.D. } 2421586.899\pm0.196$$
$$a\sin i=3{,}012{,}700 \text{ km}$$
$$\frac{m_1^3\sin^3 i}{(m+m_1)^2}=0.0113\ \odot$$

The differences between the observed radial velocities and those computed from these elements are shown in Table I under $O-C_3$.

The parallax of Boss 593 has been determined by van Maanen and by Miller. The weighted mean of the results gives an absolute magnitude of 4.2.

THE ORBIT AND ABSOLUTE DIMENSIONS OF W URSAE MAJORIS[1]

The variable star W Ursae Majoris ($\alpha = 9^h\ 36^m.7$; $\delta = +56°\ 25'$; 1900) has attracted much interest since its discovery in 1903 by Müller and Kempf, who found its light to vary in the unusually

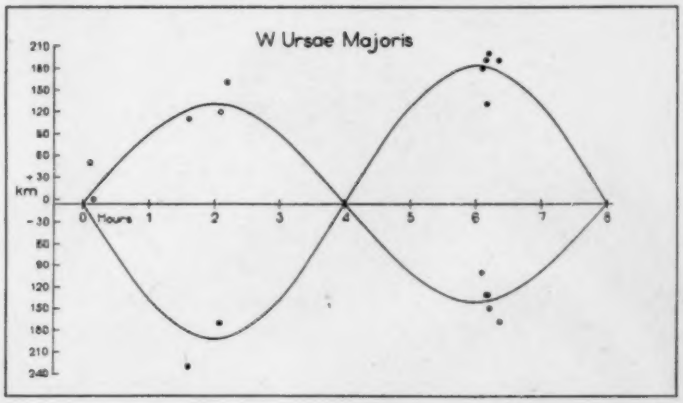


FIG. 2

short period of four hours. The variation was found to be continuous, with very sharp minima and rather flat maxima. The peculiar shape of the light-curve led Russell to apply the theory of an eclipsing binary, and he thus found that the star's light-changes might be accounted for by assuming that the period should be doubled, and that the primary and secondary eclipses produced equal minima. This result has not been as widely accepted as the evidence would warrant, probably on account of the exceptionally short period and the spectral type, which was given by the Harvard observers as Go. Hence the star is still given in some lists as a Cepheid or cluster-type variable.

[1] An abstract of this paper was read at the meeting of the American Astronomical Society, August 20–22, 1918.

The star was placed on the Mount Wilson spectrographic observing list, together with other stars of the later types having measured trigonometrical parallaxes, for the determination of absolute magnitude and parallax. Ten plates were secured from December, 1917, to March, 1918, with exposures varying from 30^m with the 7-inch camera to $2^h\ 15^m$ with the 18-inch camera. The spectra of both components appear, the lines of the primary being slightly stronger than those of the secondary. The spectrum is most extraordinary. It appears to belong to the solar type and might be classified as F8p. The faint lines are entirely obliterated, and the strong lines are so widened and weakened that measures for

TABLE II

Plate	Date			G.M.T.	Exp.	Phase	Velocity of Primary	Velocity of Secondary
							km	km
6417.....	1917	Dec.	1	22^h45^m	135^m	6^h4	−170	+190
6433.....			3	22 35	60	6.1	−130	+190
6443*.....			5	0 13	115	0.1	.....	.....
6521.....	1918	Jan.	1	1 13	45	0.2	.....	.....
6524†.....			1	19 15	30	2.2	+160	(−260)
6526.....			1	23 15	30	6.2	−150	+200
6538.....			2	23 11	38	6.1	−100	+180
6692.....		Feb.	1	19 50	56	2.1	+120	−170
6695.....			1	23 55	60	6.2	−130	+130
6820.....		March	31	20 35	70	1.6	+110	−230

* Lines of two spectra blended. Measured $V = +50$ km.

† Lines of two spectra blended. Measured $V = 0$ km.

velocity and estimates of line-intensity can be made only with the greatest difficulty. The results accordingly are given only as the best approximations which can be determined from the plates. The results of the spectrographic measures, together with the photometric orbits by Russell and Shapley, show that the unusual character of the spectral lines is due partly to the rapid change in velocity during even our shortest exposures but mainly to the rotational effect in each star, which may cause a difference of velocity in the line of sight of as much as 240 km between the two limbs of the star.

Table II gives a summary of the observations. Three plates were taken at maximum light when the primary star was receding,

five at the opposite maximum when the primary was approaching, and two near the even minima. The phases were computed from the recent light-elements by Shapley and Van der Bilt,[1] using the period of 0.3336392 day. The velocities are corrected to give the effective velocity for the whole exposure and are rounded off to the nearest ten kilometers on account of the character of the spectrum. They are the means of the measures of three and in a few cases of four observers. On plate 6524 the second component was measured by only one observer, and the value is omitted.

The following orbital elements were determined after grouping the observations according to phase and assigning weights according to the character of the lines:

Eccentricity, e (assumed) $= 0.00$
Velocity of center of mass, $\gamma = -5 \pm 13$ km/sec.
Semi-velocity range of primary, $K_1 = 134 \pm 5$ km/sec.
Semi-velocity range of secondary, $K_2 = 188 \pm 15$ km/sec.
Radius of orbit of primary, $a_1 \sin i = 610{,}000$ km
Radius of orbit of secondary, $a_2 \sin i = 860{,}000$ km
Mass of primary, $m_1 \sin^3 i = 0.67\ \odot$
Mass of secondary, $m_2 \sin^3 i = 0.48\ \odot$
Ratio of masses, $\frac{m_2}{m_1} = 0.71$

With the aid of Russell's solution of the photometric orbit as given by Shapley[2] we may now compute the absolute dimensions of the orbit and the individual stars and find the masses and densities of each star, thus giving data which are known for only a very few stars.

Taking the "uniform" solution which Russell suggests as the most probable because of the color-indexes found by Shapley, we note that the stars are ellipsoids with the same dimensions. The inclination $i = 77^\circ\ 35'$, and the ratio of the axes of the ellipsoids are given, whence we find:

Radius of the primary orbit $= 620{,}000$ km
Radius of the secondary orbit $= 880{,}000$ km

[1] *Mt. Wilson Contr.*, No. 140; *Astrophysical Journal*, 46, 290, 1917.

[2] *Contributions from Princeton Observatory*, No. 3.

Radius of the relative orbit = 1,500,000 km
Greatest semi-axis of each star = 548,000 km = 0.78 sun's radius
Intermediate semi-axis of each star = 408,000 km = 0.58 sun's radius
Polar semi-axis of each star = 373,000 km = 0.54 sun's radius
Mass of primary = 0.69 ⊙
Mass of secondary = 0.49 ⊙
Density of primary = 2.8 ⊙
Density of secondary = 1.9 ⊙

The densities are remarkable as being the highest known in any stellar system. The projected surface area of the two stars is equal to about 90 per cent of the sun. If we should assume that the same surface luminosity prevails on the stars as on the sun, as we should expect in similar spectral types, the absolute magnitude would be about 4.8 (calling the sun 5.0) and the parallax 0".024.

The trigonometric parallax has been measured at the Yerkes Observatory and found to be 0".012, corresponding to an absolute magnitude of 3.3, and our rough estimates from the very poor spectral lines seem to agree with it. If then we accept the measured parallaxes, we find the surface luminosity of the stars to be four times that of our sun.

THE ORBIT AND ABSOLUTE DIMENSIONS OF Z HERCULIS

The Algol variable Z Herculis ($\alpha = 17^h\ 53^m.6$; $\delta = +15°\ 9'$; 1900) is well known because its period is so nearly equal to four days that it has been found difficult to make complete observations of its light and velocity changes at any one observatory. In the course of the observation of stars with measured parallaxes nine spectrograms have been secured at Mount Wilson. These observations have been timed in such a way that they allow a determination of the spectrographic orbit, if it is assumed to be circular in accordance with the photometric orbit computed by Shapley.[1] Both the photometric and spectrographic results indicate that in general the Algol variables move in orbits which are nearly circular. The star R Canis Majoris,[2] $e = 0.138$, is the only one thus far

[1] *Contributions from Princeton Observatory*, No. 3, p. 100.

[2] Jordan, *Publications of the Allegheny Observatory*, 3, 49, 1912.

found to have an eccentricity of more than 0.100. Plate 6942, which was taken near minimum of light, was of inferior quality and was not used in the solution.

Two spectrograms taken by Frost[1] in 1905 give velocities which fall fairly well on our curve and show that the period has been accurately determined. Our photographs show the presence of two spectra of type F2. The lines of the secondary spectrum are

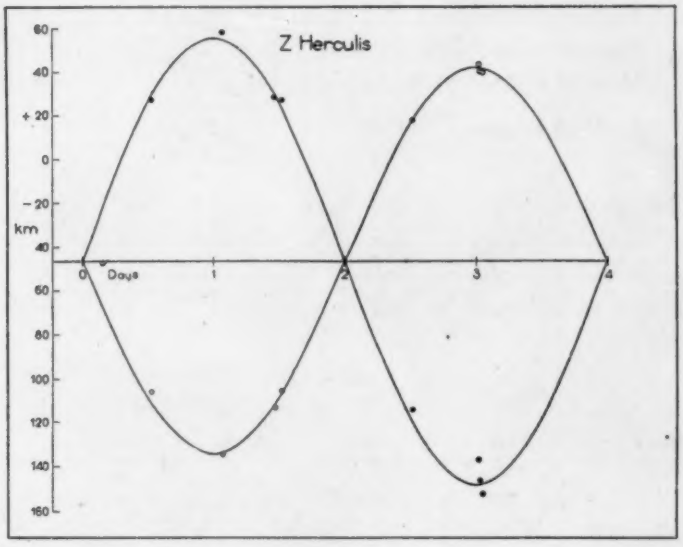


FIG. 3

only about one-half as strong as those of the primary, and many are poorly defined or not seen at all on some of the plates. The orbit of the secondary is consequently less accurately determined. Although the results show that there is a marked difference in surface luminosity between the two stars, the spectra appear to be essentially of the same type. The rotational effect is so small that the spectral lines are fairly sharp, and measures of the primary show good agreement. The velocity of the center of mass is unusually large.

[1] *Astrophysical Journal*, 22, 214, 1905.

The following elements were determined, the orbit being assumed to be circular:

Photometric period, $P = 3.992775$ days (Lehnert)
Eccentricity, $e = 0.00$ (assumed)
Velocity of center of mass, $\gamma = -46.5 \pm 0.3$ km/sec
Semi-velocity range of primary, $K_1 = 88.2 \pm 0.4$ km/sec
Semi-velocity range of secondary, $K_2 = 101.8 \pm 1.4$ km/sec
Radius of primary orbit, $a_1 \sin i = 4{,}800{,}000$ km
Radius of secondary orbit, $a_2 \sin i = 5{,}600{,}000$ km
Mass of primary, $m_1 \sin^3 i = 1.5 \odot$
Mass of secondary, $m_2 \sin^3 i = 1.3 \odot$
Ratio of masses, $\frac{m_2}{m_1} = 0.86$

The photometric orbit has been computed by Shapley[1] from observations by Wendell at Harvard. On account of the peculiarity of the period the observations of different portions of the light-curve had to be made in different seasons, but the results were

TABLE III

Plate	Date	G.M.T.	Phase	V_1	V_2
			Days	km	km
6265.....	1917 Oct. 5	15^h46^m	0.514	−106.0	+ 27.1
6273.....	6	15 44	1.512	−106.8	+ 27.5
6300.....	26	14 13	1.466	−113.0	+ 28.6
6357.....	Nov. 4	14 38	2.507	+ 17.4	−114.7
6933.....	1918 May 25	19 10	1.075	−134.9	+ 58.0
6939.....	27	18 40	3.054	+ 39.5	−152.7
6942.....	28	21 5	0.162	.....	− 47.2
7070.....	June 24	16 55	3.031	+ 43.7	−137.0
7134.....	July 18	16 47	3.049	+ 39.8	−146.4

considered fairly reliable. The "uniform" solution gives a grazing total eclipse and the "darkened" solution a partial eclipse, with the larger star in front in both cases. The larger star is the fainter. The secondary eclipse is very shallow. Combining the results of the spectrographic observations with the photometric we obtain the absolute dimensions of the orbits and of the individual stars.

[1] *Contributions from Princeton Observatory*, No. 3, 1915.

The photometric observations are not sufficient to give the relation of the axes of the ellipsoids.

TABLE IV

	"Uniform" Solution	"Darkened" Solution
Inclination of orbit	83° 40′	82° 0′
Radius of primary orbit	4,870,000 km	4,880,000 km
Radius of secondary orbit	5,620,000 km	5,640,000 km
Radius of relative orbit or distance of centers	10,490,000 km	10,520,000 km
Radius of bright primary star	1,020,000 km	1,230,000 km
Radius of faint secondary star	2,170,000 km	2,290,000 km
Mass of primary	1.5 ⊙	1.6 ⊙
Mass of secondary	1.3 ⊙	1.3 ⊙
Density of primary	0.5 ⊙	0.3 ⊙
Density of secondary	0.05 ⊙	0.04 ⊙

The absolute magnitude of the brighter star determined from the spectra is +2.4, indicating a parallax of 0″.010, which is in good agreement with the hypothetical parallax. The trigonometric parallax as determined at the Yerkes Observatory is +0″.033.

MOUNT WILSON SOLAR OBSERVATORY
February 1919

Minor Contributions and Notes

THE SPECTRUM OF COMET MELLISH (1915*a*)

Two series of objective-prism plates were taken at this observatory, beginning June 5 and ending August 20, 1915. The series by Mr. R. Winter was taken with a 60°-prism attached to a two-inch lens of six inches focal length, giving a linear dispersion of 9 mm between λ 3600 and λ 5200.[1] The other series, by Mr. F. Symonds, was taken with a 20°-prism placed before a five-inch lens of 25 inches focal length, giving about three-fourths as much dispersion.[2] The plates are Capelli, extra rapid. Tables I and II give a brief record of the plates.

This series includes plates taken in July and August, but the images are weak and show practically nothing of the tail.

The spectrum of a star giving the usual hydrogen lines was selected as a standard of dispersion for the plate, and a bright knot at the violet end of the comet spectrum was assumed to be at λ 388. Simple estimation of the relative positions of the comet's radiations and the hydrogen lines gives the following approximate wave-lengths and their identification:

	Description	Identification
λ 388	very bright knot	Third cyanogen band
400	tail band	Low pressure CO
403	knot	
422	faint knot	Second cyanogen band
427	tail band	Low pressure CO
436	knot	Fifth carbon band
456	tail band	Low pressure CO
468	bright knot	Fourth carbon band

It is at once evident that, except for minor differences in relative intensities, the spectrum of Comet Mellish is an excellent

[1] Attached to the astrographic telescope.

[2] From June 5 to July 8, inclusive, the apparatus was attached to the 12-inch equatorial, then it was put on the Heele photographic telescope.

reproduction of the spectrum of Comet Brooks (1911*c*), which was studied in considerable detail by W. H. Wright.[1]

TABLE I

SERIES BY F. SYMONDS

Plate	1915	Exp.	Description
6151	June 7	$1^h\ 20^m$	Image strong, but not sharp. 2° tail
6158	11	2 0	4° tail
6162	12	0 33	
6163	12	2 0	4° tail
6170	14	0 30	
6171	14	1 30	5½° tail
6194	July 6	1 50	Poor focus, plate fogged, no tail
6197	8	2 0	Poor focus, plate fogged, no tail
6198	17	1 50	Tail short
6202	20	2 30	Plate fogged
6205	21	1 27	2° tail
6214	Aug. 11	1 55	2° tail
6217	12	2 05	Plate fogged
6218	15	2 0	Plate fogged
6228	18	2 0	Tail short
6231	19	2 0	2° tail

TABLE II

SERIES BY R. WINTER

Plate	1915	Exp.	Description
6143	June 5	$1^h\ 0^m$	Short tail
6146	6	1 29	Short tail
6147	6	0 35	
6149	7	1 59	
6153	10	2 17	
6154	10	0 30	
6156	11	2 0	Tail longer
6157	11	0 31	
6162	12	1 34	
6163	12	0 31	
6167	14	1 44	
6169	14	0 31	
6172	16	1 43	9° tail
6174	16	0 43	
6175	17	1 30	9° tail
6177	17	0 33	
6178	20	1 06	9° tail
6180	22	2 0	Plate of same density as No. 6178 but tail is very short
6182	22	0 33	
6183	23	0 02	Very dense, tail very short
6186	24	1 34	Tail very short

[1] *Lick Observatory Bulletin*, No. 7, 8–16, 1912.

There is a pronounced increase in intensity and length of the tail band from June 5 to June 17, and it might be expected that these series of plates would show the relation of the development of the tail bands to the comet's approach to the sun. Unfortunately they do not. Perihelion occurred on July 17, but from June 22 on the plates show little or no tail. Only two plates, one on August 11 and one on August 19, show as much as two degrees of tail. The general weakness of the images is largely due to the comet's increasing geocentric distance, and in the latter part of July to a fogging of plates by moonlight. Yet there seems to have been an abrupt decrease in intensity of the spectrum between June 20 and June 22, which is not confirmed on the direct photographs taken on these dates.

The continuous spectrum extends from about λ 3600 to λ 5200 A, but is very weak on either side of λ 388.

The knots at λ 388 and λ 468 are always considerably the strongest, but they vary in relative intensity. Early in June λ 388 was considerably the stronger. About the middle of June λ 388 was scarcely any brighter, if at all. On June 22 and following, λ 388 was always considerably the brighter.

The first few dates in June show the knot at λ 403 rather strong, but it gradually diminished in brightness until it was hardly distinguishable. The spectrum of Comet Mellish was observed at the Lowell Observatory by Slipher,[1] and he gives a group of lines in the region for which my measure is doubtless a mean. The lines which Slipher measures are also found in Comet Zlatinsky (1914*b*) and Comet Brooks (1911*c*). It seems not improbable that they can be identified with a new hydrocarbon band recently detected in the region λ 4107 and λ 4025 by C. W. Raffety.[2]

Between June 14 and June 16 the comet was subject to a pronounced outburst. From a straight quiescent type of tail there developed suddenly two bright tails, one long and divergent, the other short, curved, and well inclined to the main tail. The division of the tail is well marked on the spectrogram for the night.

[1] *Lowell Observatory Bulletin*, No. 74, **2**, 151, 1916.

[2] *Phil. Mag.* (6), **32**, 555, 1916.

The bright cyanogen knot at λ 388 extends in the direction of both tails.

A similar action took place on June 20 and is faithfully recorded in the cyanogen band at λ 388.

A. Estelle Glancy

Observatorio Nacional Argentino, Córdoba
February 20, 1918

SOME PECULIARITIES OF NOVA AQUILAE III OF 1918

At one stage of its decline Nova Persei of 1901 presented a perfectly planetary disk in the large telescope. Its light was also dull and planetary, resembling that of Neptune and some of the larger asteroids.[1] One would have instantly picked it out as differing from all the other stars.

Nova Aquilae III of 1918 has similarly shown in its decline a sharply defined planetary disk of measurable size wholly different from the image of any ordinary star. This disk was measured on a number of nights. Though in most cases the atmospheric conditions were not good for such work, the results, I believe, are fair. No one would have failed at a glance to recognize the nova as entirely different from the other stars. The striking difference between it and the ordinary star was apparent on each night by an examination of B.D.+0°4027 and 4 Aquilae, and frequently θ Serpentis. These stars showed the ordinary stellar image. Following are the measures of the diameter of the disk.

Date	C.S.T.	Diam.	
1918 Oct. 5	$6^h\ 0^m$	0".81	
12	5 40	0.54	
15	5 40	0.60	
Nov. 2	6 0	1.36	
5	5 20	1.26	
12	5 40	1.30	
23	5 15	1.02	
26	5 5	1.18	
Dec. 14	5 20	1.82	Very low
17	5 20	1.86	Very low
Mean.....		1.18	

[1] See *Astrophysical Journal*, 14, 155, 1901.

This disk seemed to become larger as if growing, as shown by the measures. The conditions were seldom good enough for the best results. I think, however, that these diameters will fairly represent the size of the image. The following notes were made at the time of the measures, Central Standard Time being used.

1919. Sept. 17, 6^h40^m. The nova has a small planetary disk of a pale yellowish-white color. Clouds prevented measures.

Oct. 5, 6^h0^m. The light of the nova is dull and planetary and of a slightly yellowish cast. The image is a perfectly planetary disk entirely different from the image of B.D. $+0°4027$. The out-of-focus image is scarlet and well defined and smaller than the focal image. This scarlet image is surrounded by a greenish-yellow glow $2''$–$3''$ in diameter.

Oct. 12, 5^h40^m to 6^h0^m. The disk is planetary, pale white or slightly yellowish, and is imbedded in a broken yellow glow. Measures of the focus of the nova and of B.D.$+0°4027$ showed only 0.2 mm difference.

Oct. 15, 6^h0^m. The disk is beautifully planetary and sharply defined, dull white with a suggestion of yellow. It is surrounded by a close yellowish halo. The crimson image at the second focus is smaller than the regular image and well defined. It is surrounded by a greenish-white halo.

Nov. 2, 6^h0^m. Seeing bad. The image is planetary—a yellowish-white disk. The crimson image is strong. Clouds.

Nov. 5, 5^h20^m. Planetary; yellowish-white disk.

Nov. 12, 5^h35^m. The image is pale yellowish color with much strong light about it. Seeing very poor.

Nov. 23, 5^h15^m. Planetary disk. Pale white color with only a suggestion of yellow. Seeing very poor.

Nov. 26, 5^h10^m. Planetary disk well seen in moments of steadiness. Pale white with yellowish cast.

Dec. 14, 5^h20^m. Seeing very poor. The disk is planetary in moments of steadiness.

Dec. 17, 5^h20^m. The disk is planetary. Pale white or bluish white. Seeing poor.

The crimson image referred to is due to the α hydrogen line in the spectrum of the star, and seems to be always present in the novae at a certain stage of their decline. This image in the 40-inch telescope is 9 mm outside the regular focus.

I have observed the magnitude of the nova on about 130 nights. These observations were made with the naked eye, with Zeiss field-glass, with the 4-inch finder of the 40-inch telescope, and with the 5-inch guiding telescope of the Bruce Observatory.

In the instruments the nova and B.D.+0°4027 were visible at the same time. A striking peculiarity in its brightness has developed in the later observations. Very different results are obtained with the different instruments: apparently the smaller the instrument, the brighter the nova. Twilight and dawn also play an important part in the relative brightness of the star: the brighter the sky, the less bright the nova. Between the various instruments and the condition of the sky results may be obtained that differ by a large part of a magnitude.

These peculiarities have been more strongly marked since the morning observations began and especially since the position of the nova has permitted it to be seen on a dark sky. At the first glance in the telescope (on a dark sky) one gets the impression that the nova is decidedly brighter than B.D.+0°4027 ($6^{M}.3$), but a more careful inspection shows that it is really less bright than that star. The image of the nova is white and closely surrounded by a rather dense glow or haze and the star itself is very ill defined, while +0°4027 is sharply defined and free from glow and is slightly yellow. The smaller the telescope, the more this stray light enters into the image and hence the brighter the star. As the sky becomes brighter the effect of this extra light upon the eye becomes less and the star appears fainter. The peculiar appearance of the light of the nova, Professor Frost informs me, is doubtless due to the great strength of the hydrogen lines in its spectrum; this, in a refracting telescope, produces an image that is ill defined and hazy.

The planetary condition of the image must also enter to a certain extent into the relative brightness of the nova with different instruments. From my observations it would seem that from these various causes estimations of the brightness of this star may at one and the same time differ by nearly a whole magnitude. This was strongly shown on February 11, 1919. On this date, when I first examined the nova with the 5-inch Bruce telescope it seemed to be about half a magnitude brighter than +0°4027. It was surrounded by a close, rather dense, hazy glow and was very white and ill defined, while the other star was slightly yellowish and well defined. At $17^{h}\ 35^{m}$, however, a closer examination showed that the image was of about the same brightness as that of +0°4027 or

possibly a little fainter. At 17^h50^m, with the field-glass, there was a striking difference in the brightness of the two stars, the nova being $0^M.4$ the brighter. At 18^h10^m it was again examined with the 5-inch on a dawn-lit sky. The nova was decidedly the fainter of the two—the estimated difference in brightness being $0^M.5$. These observations were repeated on February 17 at 16^h50^m. The first glance at the nova in the 5-inch gave the impression that it was decidedly brighter than $+0°.4027$, but a more careful inspection showed that it was about $0^M.4$ less than that star. Immediately after, the field-glass showed the nova to be $0^M.5$ the brighter of the two stars. It would seem, therefore, that from the nature of its light, estimates of the relative brightness of the nova are now likely to be discordant, depending on the size of the instrument, the brightness of the sky, etc. I have sometimes noticed with the five-inch telescope that if the nova was the fainter of the two stars for sharp focus, it became the brighter when they were out of focus.

Recent photographs with the 6-inch and 10-inch Bruce lenses make the nova slightly brighter than B.D.$+0°.4027$. Sometimes the image with the 6-inch is a little brighter than that with the 10-inch. My last evening observations were made on December 19, 1918. The first morning observations were on January 7, 1919, near the time of its conjunction with the sun. It is an interesting fact that the star would have been observable at the time of its conjunction with the sun if weather conditions had permitted.

E. E. BARNARD

YERKES OBSERVATORY
February 21, 1919

A PROPERTY OF THE PHOTOGRAPHIC PLATE ANALOGOUS TO THE PURKINJE EFFECT

The "Purkinje Effect" in reference to visual photometry may be described thus: If two sources of light, one white, the other red, appear equal at a certain intensity, they will not remain equal if the intensity of both sources be changed in the same ratio. For example, if the intensity of each is doubled, the red will appear

brighter than the white light; or, if the intensities are halved, the red will appear fainter than the white. This is equivalent to saying that the "contrast" appears greater in the red than in the white light. It also follows that as the intensities increase, the maximum sensitiveness of the eye shifts toward the red; or, if intensities decrease, the maximum shifts toward the blue.[1]

Numerous investigators have tested the photographic plate for a corresponding effect. Abney[2] finds that "the least steep gradation is that given by the monochromatic light to which the simple silver salt experimented with is most sensitive, and that the gradation becomes steeper as the wave-lengths of light employed depart in either direction in the spectrum from this point; the steepest gradation being given by the extreme red." His graphs in Fig. 5 of that paper show the gradation to be least steep at wave-length about 4600 A, and at 6000 A to be about 50 per cent steeper.

It is important to note that this change in gradation is in the same direction as occurs in visual comparisons; an increase in intensity favors the red light, both to the eye and on the photographic plate.

The implied shift in the wave-length of maximum sensitiveness on the plate has been independently confirmed by the work of a number of observers[3] on the "effective wave-length" of light from stars of different colors.

Lindblad has summarized his results in Fig. 2, page 26, of that paper and compared these with the accordant results of the other two authors quoted. With one exception his curves lead to the same conclusion as the work of Abney; that is, as the intensity of the light increases, the position of the maximum sensitiveness shifts toward the longer wave-lengths.

[1] See Nutting's *Outlines of Applied Optics*, p. 122, Fig. 34 and p. 128.

[2] *Proceedings of the Royal Society*, **68**, 302, 312, 1904.

[3] O. Bergstrand, "Recherches sur les Couleurs des Étoiles fixes," *Comptes rendus*, **148**, 1079, 1909; E. Hertzsprung, "Über die Verwendung photograph. effektiver Wellenlängen zur Bestimmung von Farbenäquivalenten," *Pub. der astrophys. Obs. zu Potsdam*, **22**, 1, 1911; B. Lindblad, "Die photographisch effektive Wellenlänge als Farbenäquivalent der Sterne," *Arkiv för Matematik, Astronomi och Fysik*, **13**, 26, 1918.

It would thus appear that this property of the photographic plate is sufficiently confirmed in a qualitative way by these entirely independent investigations. It is the purpose of this paper to find provisional, or at least limiting, values for the amount of error which might arise from this property in photographic stellar photometry.

It is possible to derive approximate values for the difference in gradation which may be met in practice by combining Abney's results with Lindblad's. The former finds an increase of 30 to 50 per cent in gradation for an increase of 1400 A in the wave-length of the monochromatic light. Bergstrand and Hertzsprung find effective wave-lengths as follows:

	Bergstrand	Hertzsprung
White stars	4200 A	4200 A
Yellowish-red stars	4500	4300
Deepest red stars	4700	4400

Here is an extreme difference of 500 and 200 A, respectively, for white and deepest red light. We might therefore expect a change in gradation ranging between 11 and 18 per cent from Bergstrand's results, or from 4 to 7 per cent from Hertzsprung's values. Approaching from another direction, Lindblad finds for white stars an extreme shift in effective wave-length of 100 A for the greatest change in intensity of light on his plates. For stars of other colors the range is less. We might therefore look for an increase of from 2 to 4 per cent in gradation on account of change in intensity. It does not seem likely that these results are more divergent than would be expected from the use of different telescopes, plates, and developers.

A much better determination of this change in gradation can be derived from some of the extra-focal plates taken at this observatory with the Zeiss UV camera of 14.5 cm aperture and 81.4 cm focus. Two plates of the cluster in Coma, including an ideal range of star-colors, were used for this purpose.

No.	Date	G.M.T.	Exposures
UV 523	1909, May 6	$14^h\,21^m$ to $14^h\,40^m$	1^m, 2^m, 4^m, 8^m
UV 524	1909, May 7	15 00 to 15 17	15^s, 30^s, 1^m, 2^m, 4^m, 8^m

The measures and reductions were in all respects like those described by the writer in the "Yerkes Actinometry,"[1] except that only relative magnitudes were derived, all that were needed to fix the gradation of the plates. In Table I, which gives a summary of the measures of the plates, this "gradation" is expressed by the differences in apparent magnitude (ΔM) between the successive exposures.

TABLE I

Spectral Class	No. Stars	ΔM					Mean ΔM		
		UV 523			UV 524		523	524	Both
		8^m-4^m	4^m-2^m	2^m-1^m	8^m-4^m	4^m-2^m			
Ao to A5	7	0^M48	0^M79	0^M58	0^M71	0^M72	0^M62	0^M71	0^M67
F to G.....	3	0.41	0.78	0.42	0.64	0.71	0.60	0.68	0.65
K5.....	1	0.45	0.84	0.63	0.73	0.66	0.64	0.70	0.68

In explanation of Table I it should be noticed that the values of ΔM for 8^m-4^m and 2^m-1^m on plate 523 are systematically smaller than for 4^m-2^m, while in the case of plate 524 no such difference occurs. This might arise from an actual difference in exposure-times for 523, or from differences in transparency; but in either case all stars were affected alike and the final results are not changed thereby. The last column of the table shows no systematic difference in the gradation depending on the color of the star, unless the slight increase of 1½ per cent between the spectral classes A and K be considered real.[2] If so, the difference is in the direction indicated by the work of the authors already quoted. We therefore reach the conclusion that for Seed 27 plates (the brand used) and extra-focal images the slight systematic effect which may be present is nearly or quite masked by the accidental errors arising principally from the lack of uniformity in the film.

[1] *Astrophysical Journal*, **36**, 169–227, 1912.

[2] An indication that this increase may be real and an excellent confirmation of the amount of increase found in the Coma plates is furnished by Hertzsprung in his "Photographische Helligkeitsmessungen von T Vulpeculae 1910–15," *Astronomische Nachrichten*, **208**, 53, 1919, which appeared after the foregoing was in type. He finds a gradation 3 per cent steeper for the red star B.D.+27°3911 than for the neighboring white star +27°3868. The color-indices of these stars are 2^M34 and 0^M22 respectively. The plates used were Schleussner "blaue Etikette."

Summary.—A property analogous to the "Purkinje Phenomenon" has been found by Abney and other investigators to be present in the photographic plate, but the amount of the error introduced by neglecting it on Seed 27 plates and with extra-focal images is of the same order as the accidental errors.

J. A. PARKHURST

YERKES OBSERVATORY
February 19, 1919

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